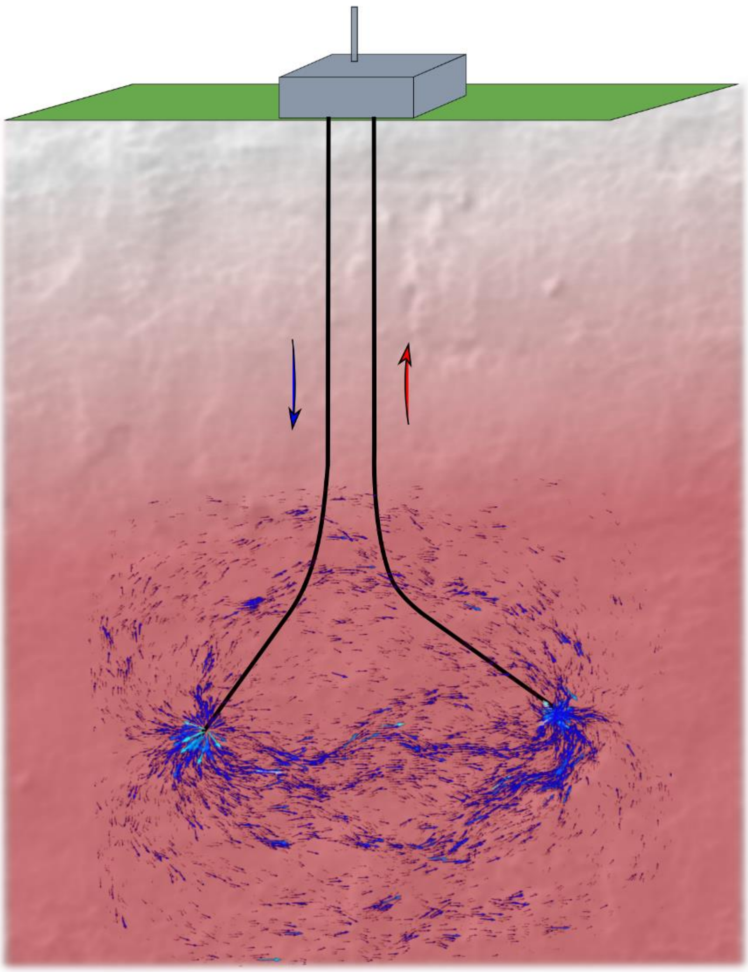
INSTITUTE OF SEISMOLOGY
UNIVERSITY OF HELSINKI

REPORT S-70

Report on deep hole drilling in geothermal energy projects, associated environmental perspectives and risk management

Guidelines for permit authorities



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Abstract

This report is intended to serve as background material for authorities monitoring and permitting geothermal plants and their environmental impacts. Geothermal energy is a renewable energy source extracted from bedrock. Extraction of heat from old and cold Finnish bedrock is challenging and requires new technological solutions. One of the prerequisites for building a geothermal plant is deep drilling, and in some cases hydraulic stimulation, which may entail a seismic risk requiring special measures. Other factors to be considered are the safety of water bodies and groundwater areas, as well as processing of the drilling and fluid wastes during construction and production phases.

This report was commissioned and funded by the Ministry of the Environment. It is written by experts from the Institute of Seismology and the Geological Survey of Finland. The aim of the report is to describe the problems and potential risks associated with deep drillholes and their usage in geothermal energy supply. The report provides permit authorities with recommendations on good practices and guidelines on permitting of the different phases of geothermal energy projects following Land Use and Building Act (132/1999). These recommendations are not binding.

The first three sections of the report provide information on seismic activity and seismic monitoring in Finland, the different forms of geothermal energy and lessons learned in projects carried out in Finland by 2019. The fourth section focuses on the risk management of induced seismicity. It includes basic information on the mechanisms of induced seismicity, ground motions, risk analysis and the seismic monitoring of plants. The earthquake risk associated with a geothermal plant is at its highest when the water permeability of the bedrock is improved via hydraulic stimulation during the construction of the plant. During this phase, operations should be especially closely monitored.

The fifth and sixth sections of the report provide recommendations concerning the content of permit applications, communications and the monitoring of operations. The permit application should include a seismic risk assessment of the plant area and its surroundings as well as the other potential environmental impacts of the power plant. It should also include plans for seismic monitoring, environmental monitoring, work site arrangements, drilling technique, the monitoring of operations and communications. Following lifecycle of the plant, the recommendations of the monitoring of operations are divided into three phases: the construction phase (including drilling and stimulation), the production phase and follow-up monitoring. Each phase is further divided into seismic monitoring and other environmental monitoring.

All of the recommendations are also presented as concise summaries at the end of the report.

Contents

Abbreviations used

ATLS – Adaptive Traffic Light System

BAT – Best Available Techniques

BREF – Best Available Techniques Reference Document

CO_2 – Carbon dioxide

DSHA – Deterministic Seismic Hazard Analysis

EGS – Enhanced Geothermal System

ELY Centre – Centre for Economic Development, Transport and the Environment

FENCAT – Fennoscandian earthquake catalogue

GRID – Geothermal Risk of Induced seismicity Diagnosis

GSF – Geological Survey of Finland

LUBA – Land Use and Building Act

PGA – Peak Ground Acceleration

PGV – Peak Ground Velocity

PSHA – Probabilistic Seismic Hazard Analysis

RIL – Finnish Association of Civil Engineers

STUK – Finnish Radiation and Nuclear Safety Authority

TLS – Traffic Light System

Terminology and concepts

Earthquake terminology

Azimuthal gap: The azimuth angle between adjacent monitoring stations as viewed from the epicentre. Azimuths are reported in degrees and measured clockwise from due north. The azimuthal gaps must be as small as possible (below 90°) to enable the reliable calculation of the earthquake's source parameters (hypocentre, fault-plane solution).

Epicentre: The point on the Earth's surface directly above the hypocentre of an earthquake. Its coordinates are reported in latitude and longitude.

Hypocentre: The focus of the earthquake, where the strain energy is first released. Includes coordinates and the depth at which the earthquake occurred.

Induced earthquake: An earthquake that is caused solely by human activity that alters the stress conditions on the Earth's crust and would not have occurred otherwise. Activities such as underground excavation, the weight of water masses near large reservoirs and the injection of water into the bedrock alter the underground stresses and can, thus, induce earthquakes.

Aftershock: A smaller earthquake that follows a larger earthquake in the same area. Large earthquakes may have several, even hundreds of aftershocks.

Natural/tectonic earthquake: The shaking of the ground caused by the sudden release of strain energy stored in the bedrock.

Micro-earthquake: A small earthquake that is usually detected only with seismic instruments. In earthquake seismology, a micro-earthquake means an earthquake with magnitude lower than M 2–3, but in the context of hydraulic stimulation, the limit is often M 0.

Seismic wave: The waves caused by an impulse, such as an earthquake or explosion, which travel through the Earth (P and S waves) or along the Earth's surface (Rayleigh and Love waves). P waves are longitudinal waves, like sound waves. S and Love waves are transverse waves and slower than P waves. Rayleigh waves consist of both longitudinal and transverse wave motion and are the slowest type of waves. The velocity differences between different types of waves are utilised in determining the locations of seismic events. See Figure i.

Fault-plane solution: Models an earthquake with the help of two fault-planes sliding in relation to one another. A fault-plane solution describes the orientation of the fault moved (strike, measured clockwise from the north), its dip relative to a horizontal plane and the direction of the slip vector on the fault plane (rake). The solution also includes an assessment of the orientations and nature of the stress field surrounding the earthquake source.

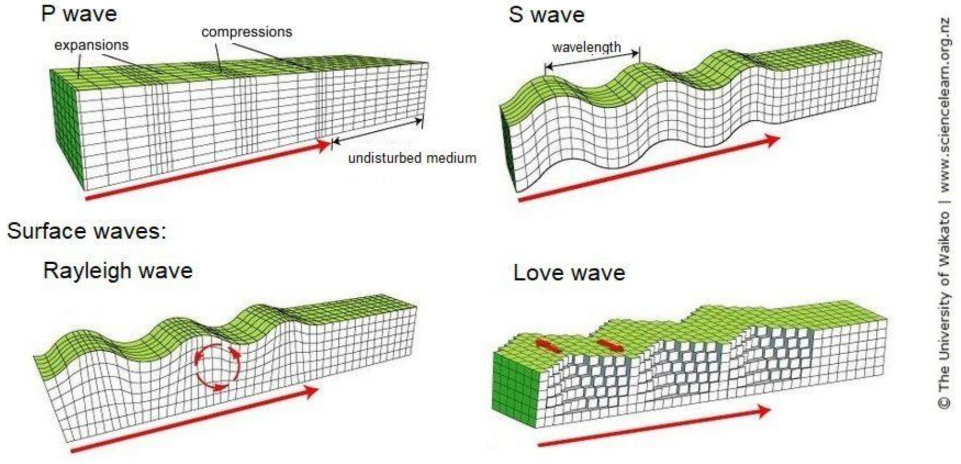

Figure i: Illustrations of seismic wave types. Source: Science Learning Hub – Pokapū Akoranga Pūtaiao, University of Waikato, http://www.sciencelearn.org.nz.

Earthquake strength

Intensity, or more precisely macroseismic intensity, describes how powerful an earthquake's effects are. It is an integer that summarises the scale of the earthquake's effects at a given location. Intensity is reported on a 12-degree scale, with each degree represented by a roman numeral. The lowest intensity perceptible to humans is II, and the highest intensity XII denotes complete devastation. Cosmetic damage starts to occur at intensity V or VI.

Magnitude denotes the strength of an earthquake at its source. Magnitude is based on the maximum ground motion recorded by a seismic monitoring station and is reported as a number on a logarithmic magnitude scale. A one-unit increase in magnitude means an approximate tenfold increase in ground motion and an approximate 30-fold increase in the amount of seismic energy released. The different magnitude scales used are scaled to give similar numerical values, so the recommendation is to use the shared symbol M for all magnitudes, unless it is necessary to specify how the measurement was conducted.

Seismic hazard describes the natural seismicity of a given area. A statistical seismic hazard assessment conventionally presents probabilities at which earthquakes of specific sizes or ground motions of specific sizes caused by them will occur in an area within a given time. The natural seismic hazard level of an area is unaffected by human activity.

Seismic risk denotes the impact of an area's seismicity on the built environment and assesses the damage and costs that a large earthquake would cause in that area. The level of seismic risk can be reduced by constructing buildings that can withstand earthquakes of specific sizes, for example.

Concepts related to the structure of the Earth

Aquifer: An underground groundwater reservoir.

Crust: The outermost layer of the Earth. It is thinnest under the oceans and thickest under continental mountain ranges. In the area of Finland, the crust is approximately 40–60 kilometres thick.

Crustal stress field: The crustal stress field is 3-dimensional and depicted by the size, direction and dip of three mutually perpendicular principal stresses σ_1, σ_2, σ_3 (maximum, intermediate, minimum). In Finland, the maximum principal stress is typically nearly horizontal and oriented in the northwest-southeast direction. The measurement results show considerable variation, especially in the surface parts of the bedrock.

Fault: A weakness point in the Earth's crust, where the bedrock has fractured and displaced. A fault is categorised as active if it has shown signs of significant motion or seismicity in the last 10,000 years.

Postglacial fault: An active fault formed after the last glacial period.

Concepts related to geothermal energy, stimulation and drilling technology

Shallow geothermal energy = ground source heat: In this report, these terms are used to describe heat transfer systems that are less than 500 metres deep.

Deep geothermal energy or **geothermal energy**: In this report, these terms are used to describe heat transfer systems that are over 500 metres deep.

Geothermal well = energy well: A heat transfer pipeline placed in a borehole. The term well is used for the boreholes of both shallow and deep geothermal plants.

Cutting, chipping: The rock dust or fragments generated during drilling.

Stimulation: The expansion of fractures for the purpose of increasing the water permeability of rock at the target depth. An umbrella term for various expansion mechanisms, such as hydraulic stimulation, which includes fracturing, induced shearing and chemical stimulation.

Hydraulic stimulation: The expansion of fractures by injecting large amounts of water into a borehole.

Fracturing: Used for the same purpose as the concept of *hydraulic stimulation*, but technically fracturing refers only to the expansion of **tension fractures** (see Figure 6, section 4.1).

Tension fracture = tensile crack: A fracture formed by tension stress (stress perpendicular to the minimum principal stress), which initially expands perpendicular to the walls of the fracture and then propagates parallel to the fracture walls (see Figure 6, Section 4.1).

1. Introduction

The utilisation of geothermal heat is a renewable and low-emission energy production method that can serve as a substitute for fossil fuels. There is a practically limitless source of thermal energy deep in the Earth's crust, which can be utilised for heating purposes. In Finland, the utilization of geothermal energy reserves requires drilling deep into the Earth's crust, where there are large enough thermal energy reserves. The geothermal energy sector is growing, and new solutions for utilising this type of heat source are being developed constantly. There are several geothermal projects currently in progress in Finland. Energy company St1's Deep Heat project in Otaniemi, Espoo has advanced the furthest so far.

The utilisation of geothermal energy is divided into shallow and deep geothermal energy production. The operating principle is based on the circulation of water in the soil or bedrock. The boreholes of deep geothermal plants can extend to depths down to 8 kilometres. In *enhanced geothermal system* (EGS), the water flow between boreholes is enhanced by expanding the natural fractures present at depth. This is done by injecting water into the bedrock at high pressure, which alters the stress conditions in the bedrock and enables the fractured interfaces between individual rock blocks to move. This motion is manifested as small micro-earthquakes, which can be detected with seismic instruments. It may also cause larger earthquakes, which primarily cause disruptive noise and vibrations in the immediate vicinity of the plant, but which may also result in minor damage to property and buildings. Because of this, the area's earthquake risk should be assessed during the planning stages and before the operation of a plant commences. The risk assessment should be kept updated throughout the lifecycle of the plant. Real-time seismic monitoring during the construction phase of an EGS plant is essential for ensuring general safety. This also benefits the operator, as a comprehensive monitoring system allows for better monitoring of the development of fracture zones. It also enables the separation of the earthquakes induced by the plant from other destructive seismic activity.

The environmental risks associated with geothermal plants situated in Precambrian bedrock have not been previously assessed in the world. A geothermal plant is not listed as a facility subject in Annex 1 of the Industrial Emissions Directive (2010/75/EU) and geothermal energy production is not considered to comprise an operations subject in an environmental permit in Annex 1 of the Finnish Environmental Protection Act (527/2014) or in the Environmental Protection Decree 713/2014. There is no BAT or BREF documentation for geothermal energy production at the EU level. Geothermal energy production facilities are neither considered to fall within the purview of the list of projects in Annex 1 of the Act on Environmental Impact Assessment Procedure (252/2017, EIA Act), and thus they are not automatically subject to the environmental impact assessment procedure.

In other words, in current Finnish legislation, the production of geothermal energy is not unequivocally considered to be an activity that is hazardous or harmful to the environment. The potential environmental impacts should be given particular attention when granting permits. Thus, the need for the environmental impact assessment procedure or an environmental permit should be considered on a case-by-case basis. In connection with the permit application for the Otaniemi heating plant, the Ministry of the Environment obliged ELY Centres to handle the issuing of instructions to cities. The City of Espoo applied guidelines for the establishment of shallow geothermal energy wells (Ministry of the Environment 2013) in the issuing of permits for the plant. In addition, the City authorised the Institute of Seismology to monitor the seismicity created by the operations generally and to assess the industrial monitoring system of the induced seismicity created by St1 and its consultants.

The widespread adoption of geothermal heating plant technology would require the relevant legislation to be reviewed and potentially to be amended with regard to the construction and operation of geothermal heating plants. In addition, the expertise of the authorities should be updated, cooperation should be improved and resources should to be allocated. From a legislative standpoint, notable issues associated with geothermal heating plants include, in particular, induced seismicity and questions regarding land use and groundwater. At the time of writing this report, the permit procedures of geothermal heating plants have been based on either an action permit in accordance with Section 126 of the Land Use and Building Act (132/1999, LUBA) or a building permit in accordance with Section 125 of the Act. However, if the station's location or some other factors trigger the environmental impact assessment procedure and/or the need for an environmental permit in accordance with the Environmental Protection Act, this must also be taken into consideration in the processing of permit applications. Permits and the parties that process them, are covered in this text on a general level. However, the applicant must ascertain, which apply to their case, before submitting their permit application,

The aim of this report is to provide the authorities of Finland with basic information on geothermal energy and the related concept of induced seismicity, as well as on the environmental impacts of deep borehole drilling. The report includes recommendations for mitigating the risks associated with induced seismicity during the construction and operation of geothermal heating plants. The guidelines have been compiled by utilising existing international research and applying it to the local geological and seismological conditions of Finland. Other resources utilised in the compilation of the guidelines include the general environmental permit procedure guidelines available on the joint website of Finland's environmental administration (www.ymparisto.fi/en-US). The report also makes use of the Institute of Seismology's experiences in the seismic monitoring of the first drilling and stimulation phase of St1 plant site. The report includes a section dedicated to communications. The main purpose of communications is to provide information of a geothermal project's background, implementation and the safety measures to the local policy-makers and public.

This report was commissioned and funded by the Ministry of the Environment, and written by experts from the Institute of Seismology and the Geological Survey of Finland. At the Institute of Seismology, the report was prepared under the direction of senior seismologist Marja Uski, PhL. Kaiu Piipponen, MSc, Katriina Arhe, MSc, and Kati Oinonen, MSc made major contributions. At the Geological Survey of Finland, the work was carried out under Teppo Arola, PhD. Jaana Jarva, PhD, Jussi Mattila, PhD, and Hannu Lahtinen, MSc made major contributions. English translation by the translation and language division of the Prime Minister's Office and the authors.

2. Seismicity and seismic monitoring in Finland

2.1 The administrative duties of the Institute of Seismology

The Institute of Seismology was established in 1961 and has since served as the authority responsible for seismic monitoring in Finland. The Institute has administrative duties related to the management of seismic risk and the enforcement of the Comprehensive Nuclear-Test-Ban Treaty, which are based on agreements and regulations. Seismic monitoring and the maintenance of a national seismic network are prerequisites for carrying out these duties. The Institute is also the organization that people contact about various vibration and sound observations in Finland, and when major earthquakes occur around the world, for example. Nowadays the majority of the queries received by the Institute are submitted electronically via an observation form available on the Institute's website.

The legislative and regulatory work related to the operation of geothermal heating plants is still in its early stages in Finland. In connection with the commercial Otaniemi heating plant project, there has been some uncertainty in the role and responsibilities of the Institute of Seismology as a supervisory body, and in how the equipment and workforce resources required for the new duties would be financed. The Institute of Seismology considers its task to be first and foremost to support supervisory, permit and regulatory authorities. But it may also take responsibility for the seismic monitoring and the seismological analysis of externally funded commercial projects, if these tasks present notable synergy benefits with the Institute's current national monitoring task. As such, it is important to define the roles and responsibilities of each participating party and funding arrangements right at the start of each individual project.

2.2 The seismicity of Finland

Finland is located in the inner part of the Eurasian Plate, far away from active plate boundaries. Natural seismicity is low in global scale, and most of the earthquakes occurring in Finland are smaller than magnitude M 4. The majority of local earthquakes occur in the upper parts of the Earth's crust, at the depths of approximately 1–15 kilometres. The seismicity of Finland is resulting from tectonic processes such as the opening of the mid-Atlantic Ridge, postglacial rebound and local variations of the stress field related to structural differences in the Earth's crust. The maximum principal stress is usually horizontal and it is oriented approximately northwest-southeast (Heidbach et al. 2016). The orientation and structure at depth dictates which faults tend to slip most easily in response to ambient stress changes (Koskinen, 2013; Mattila 2015; Kaisko 2018).

Figure 1 presents an overview of earthquakes detected in Finland and neighbouring areas in the 21st century. The most seismically active zones are marked with ellipsoids. In the northern parts of Finland, earthquakes are most frequently associated with fault zones oriented northeast-southwest or northwest-southeast. In the seismicity zone extending from the Bay of Bothnia along the Finnish-Swedish border to northern Norway (Figure 1, B), the earthquakes are related primarily to postglacial faults, i.e. faults active after the last glacial period. Another seismically active zone extends from the municipality of Kuusamo to Kandalaksha Bay in northwest Russia (Figure 1, K). It is composed of an extensive northeast-southwest-oriented fault zone and smaller faults intersecting at different directions. In the

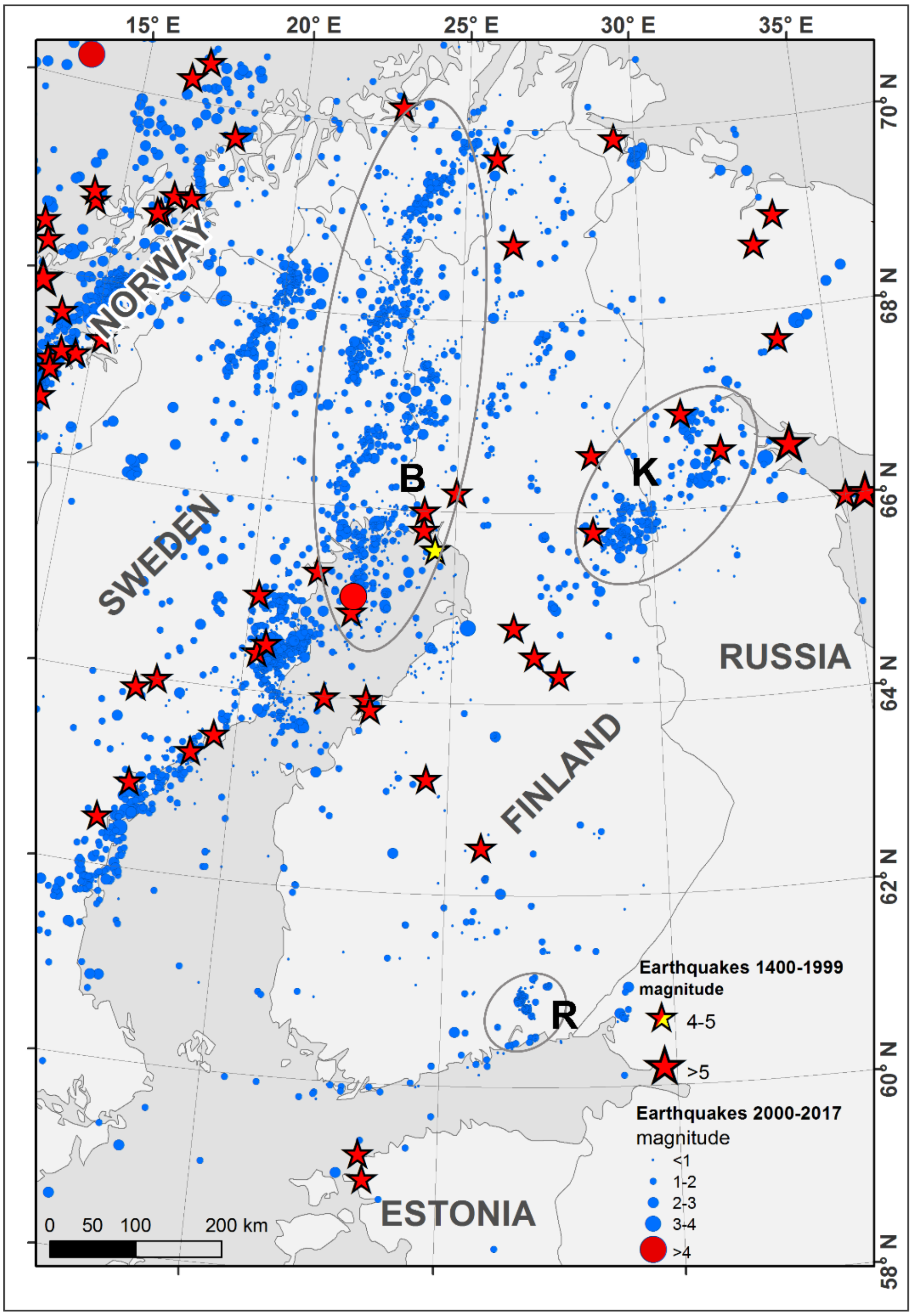

Figure 1: Current seismicity in Finland and neighbouring areas. Circles denote observations made in 2000–2017. Asterisks denote M>4 earthquakes recorded in 1400–1999. Yellow asterisk - the M 4.6 earthquake of 1882. The seismically most active areas, the Bay of Bothnia-Northern Norway (B), Kuusamo-Kandalaksha (K) and the Southeast Finland rapakivi granite area (R), are outlined in grey. Source: Fennoscandian earthquake catalogue (FENCAT, https://www.seismo.helsinki.fi/bulletin/list/catalog/FENCAT.html)

southern parts of Finland, seismic activity is more sporadic. The one exception is the rapakivi granite area in Southeast Finland (Figure 1, R), where shallow (1–2 km deep) earthquake swarms have occurred throughout recorded history. The most recent swarm in 2011–2012 consisted of over 200 events, the largest of which was magnitude M 2.9.

The largest earthquake known in the history of Finland occurred on 23 July 1882 in the Bay of Bothnia (Figure 1, yellow asterisk). Its magnitude was estimated to be M 4.6, and it caused minor damage to buildings in coastal towns (Mäntyniemi and Wahlström 2013). The largest (M 3.6) instrumentally recorded earthquake in Finland occurred on 17 February 1979 in the municipality of Lappajärvi. Figure 1 shows that the largest earthquakes are not confined only to known zones of seismic activity. In fact, many of them occurred in areas that had previously been considered to be seismically inactive. (Korja et al. 2015.)

In areas of low seismic activity, such as Finland, the activity of individual faults is difficult to predict, as earthquakes occur rarely and the recurrence time of the largest earthquakes may be up to ten thousands of years. Finnish bedrock is pervasively fractured and thus the majority of faults are short. There are also larger faults in Finland, and according to some estimates the largest faults are associated with a hypothetical risk of magnitude M 7 earthquake (Korja et al. 2015; Ojala et al. 2018).

2.3 Seismic monitoring in Finland

At present, there are over 30 permanent seismic monitoring stations in Finland, as well as temporary stations in study areas (Figure 2). Nearly all of these stations have a real-time data connection to the Institute of Seismology's automatic data management and analysis system. The Institute also receives real-time data from seismic stations maintained by the University of Oulu and by co-operative seismological agencies in neighbouring countries (Kortström et al. 2018).

The Institute of Seismology has developed an automatic, nearly real-time location system, which is based on the extraction of seismic signals from background noise, the determination of the direction of incoming signals with the help of three-component registrations and the association of observations from several stations. The system also includes an artificial intelligence-based automatic event identification method (Kortström et al. 2016), which sorts out probable earthquakes from other observations. The detection-threshold magnitude of the national seismic network is M 1. This means that the network can detect all seismic events occurring within the network with a magnitude of 1 or greater (Kortström et al. 2018). Within dense, temporary networks, the threshold magnitude may be even as low as M 0.

The Institute of Seismology locates approximately 16,000 seismic events in Finland and neighbouring areas annually. Of these, 1–2% are earthquakes, with the rest consisting primarily of explosions or collapses related to construction or mining operations. As part of daily analysis, all automatic results are checked and any earthquakes are re-analysed manually. In regard to explosions and collapses, efforts are focused primarily on the largest events that were observed by people or caused damage.

The Institute of Seismology maintains the Fennoscandian earthquake catalogue (FENCAT; Ahjos and Uski 1992, https://www.seismo.helsinki.fi/bulletin/list/catalog/FENCAT.html), which compiles earthquake observations from over six centuries. FENCAT is the region's most comprehensive open earthquake catalogue and an extensively referenced resource in seismicity studies. The Institute's observatory operations are public and transparent: seismic event data and reports are Open Access and they are published on the Institute's website, and the waveform data of nearly all permanent seismic stations is also available online (Institute of Seismology 2019).

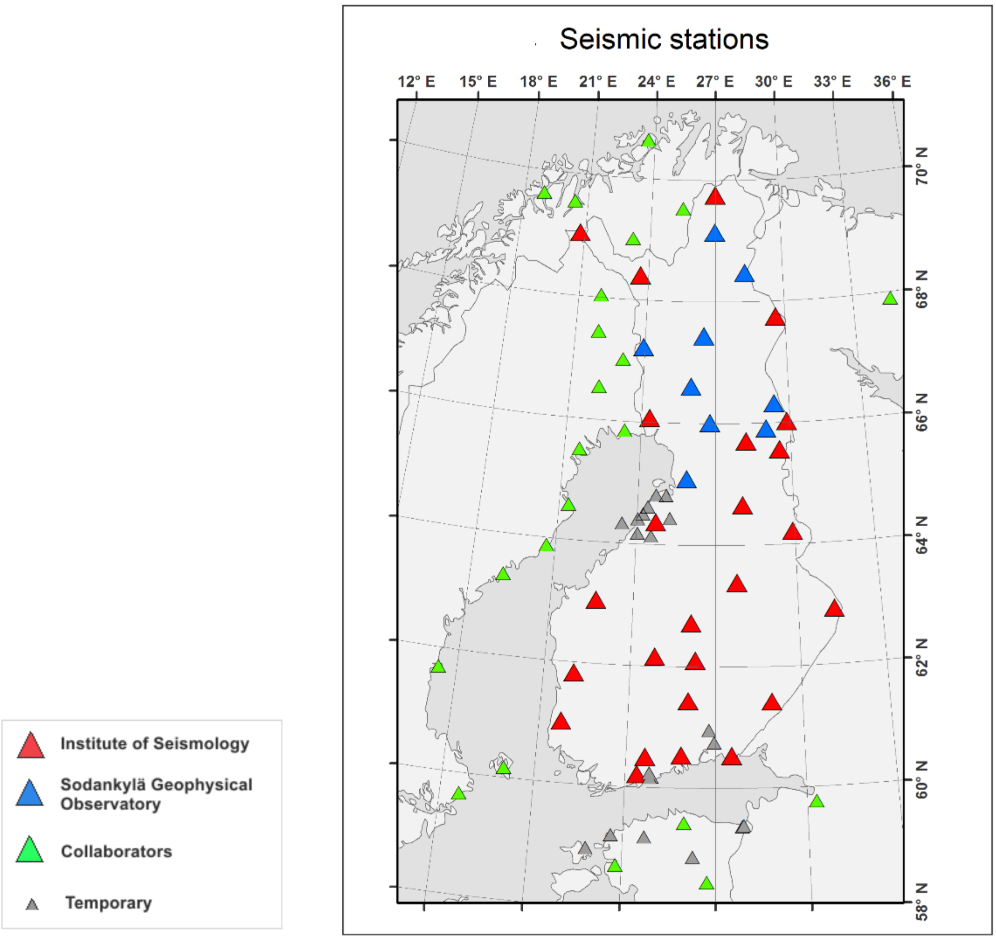

Figure 2: Finland's network of seismic stations 2018.

3. The different forms of geothermal energy

The utilisation of geothermal energy is divided into shallow and deep geothermal energy. Shallow geothermal energy can be utilised for heating and cooling purposes, while deep geothermal energy can also be used to generate electricity. In Finland, the depth limit between shallow and deep geothermal energy has established at around 300–500 metres from the ground.

Figure 3 provides an overview of the different shallow and deep geothermal energy systems suited to Finnish conditions. The systems can be either open or closed, and they may use water or some other liquid, such as denatured ethanol, for heat transfer. In open systems, the aim is to utilise the surrounding rock or a local water body for heat transfer, whereas in closed systems the heat transfer medium circulates in pipes and it does not come into contact with the surrounding rock or a water body.

Deep geothermal energy applications is a developing field of technology, and therefore the systems presented in the figure are not the only available options. This introduces the most common applications of geothermal energy currently in use.

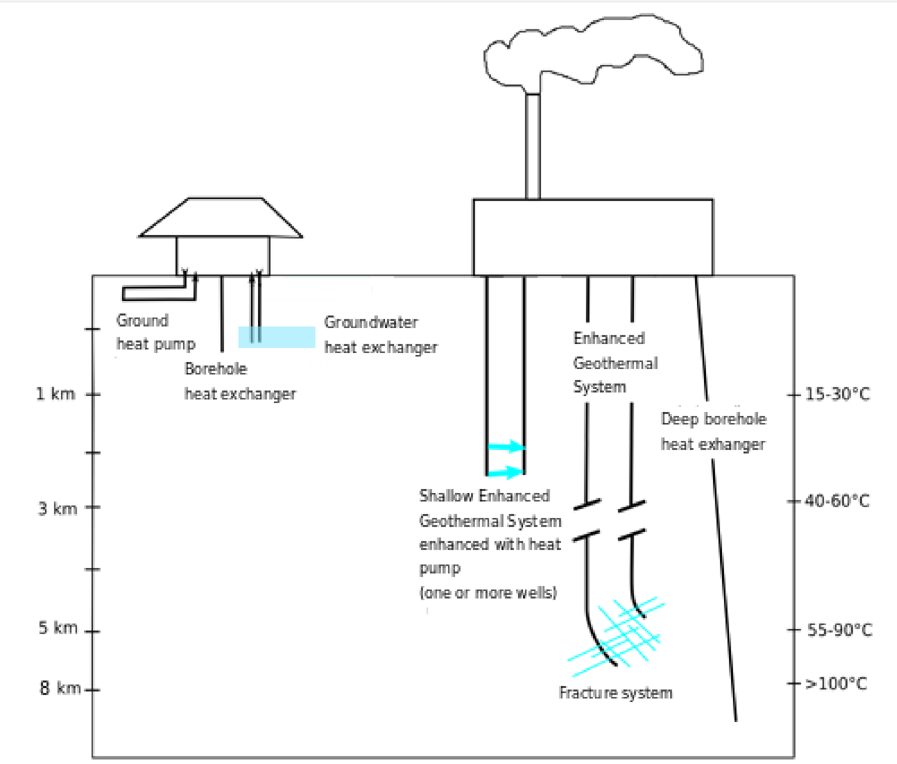

Figure 3: Different geothermal energy solutions currently being considered in Finland.

3.1 Shallow geothermal energy applications

The most common shallow geothermal energy applications are ground source heat wells. They utilise the surface layer of the ground or bedrock, which is heated both by the sun and the Earth's internal heat. A ground source heat array is a horizontal array of heat transfer pipes installed in the surface layer of the ground or in a water body. A borehole heat exchanger is a vertical tube drilled to the rock, which can house either an enclosed U-tube or a coaxial tube. In a U-tube, cold liquid is injected into the well from one end of the pipe and heated liquid is extracted from the other. In a coaxial tube, cold liquid is injected into the well along the well annulus and pumped up via the inner pipe. It is possible to leave the coaxial well partially open, for example from its bottom, in which case it can also utilise water-conducting structures present in the rock.

Borehole heat exchangers can supply the heat needed by a single-family house, and utilizing multiple wells, they can also be used to heat larger building complexes. The largest in Finland and currently third-

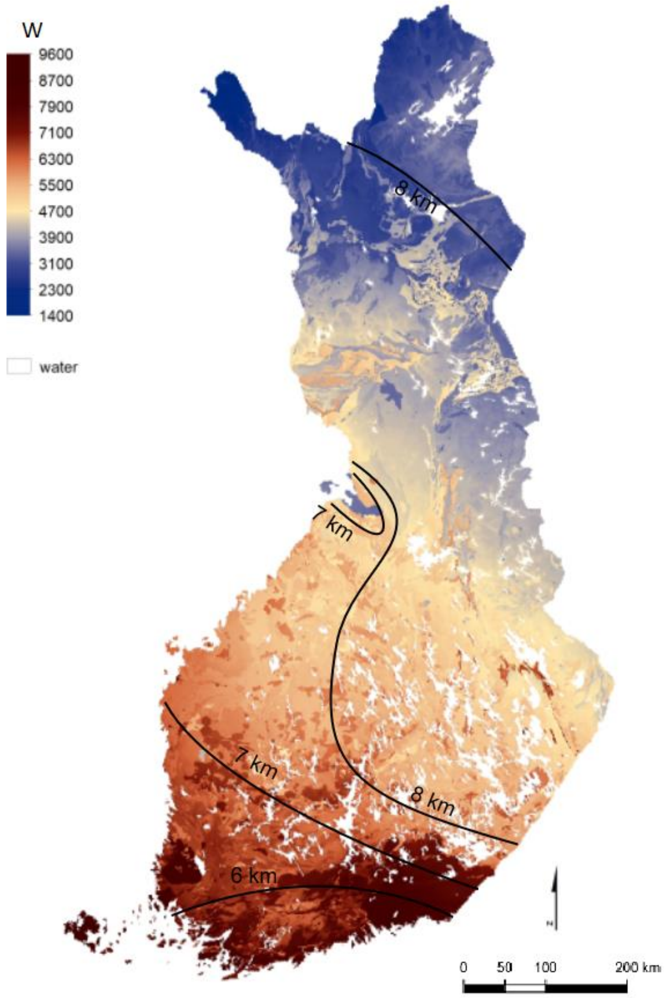

Figure 4: Renewable power in the ground in Finland down to a depth of 300 metres and the drilling depth required to reach a temperature of 100^{0}C.
Sources: GTK, https://www.gtkdata.gtk.fi/maankamara/ and Kukkonen (2000).

largest geothermal energy well system in Europe is SOK's logistics centre in Sipoo, which consists of 300 approximately 300-metre-deep energy wells. Shallow geothermal energy can also be utilised so that groundwater is pumped directly from a well into a heat exchanger. These types of systems do not have separate heat transfer arrays or mediums, as the groundwater itself serves as the energy carrier. In the simplest systems, groundwater is pumped out from one well and re-injected into the aquifer via another well. Finland's groundwaters have been identified as having significant local potential for renewable heating and cooling energy, which has so far remained nearly untapped (Arola 2015).

In recent years, there have also been some buildings commissioned in Finland that utilise geoenergy via heat exchangers installed in the building's foundation piles (Lautkankare et al. 2017). The heat source is the clay layer close to the surface of the ground.

Ground and rock source heat is a good energy source that reduces heating costs locally. The operation of a ground source heat pump consumes approximately 1/3 of the electricity required to heat an electrically heated house (Pokki et al. 2014). In Sweden, geothermal energy wells heat 20 per cent of the country's single-family houses; more than anywhere else in Europe (Gehlin and Andersson 2016). In Finland, the potential for utilising geothermal energy is greatest in the southern parts of the country (Figure 4).

3.2. Deep geothermal energy

The part of the ground that is affected by seasonal temperature differences extends to a depth of approximately 15 metres. Below this depth, the temperature increases consistently with depth, regardless of the season. This constant heat in the Earth's crust is called geothermal heat. Its primary sources are the decay of the radioactive isotopes, primarily uranium, thorium and potassium, heat generated during the accretion of the planet and the phase transition of minerals at the boundary of the Earth's core. Utilising this heat for large scale heating purposes requires drilling down to depths at which water can be heated to a temperature of at least 70°C. For electricity generation, the required minimum temperature is 150°C. However, even lower temperatures can be utilised for heating if the system is equipped with a heat pump, which is used to raise water temperature to the required minimum of 70°C. The rate at which the temperature in the Earth's crust rises with respect to the increasing depth (geothermal gradient) varies greatly by region. Whereas in volcanic areas hot water can be found even right close to the surface, in Southern Finland the geothermal gradient is approximately 2°C/100 m, while in Archaean Eastern and Northern Finland it can be as low as 1.2°C/100 m (Kukkonen 2000). What this means in practice is that reaching a temperature of 100°C requires drilling down to a depth 6–9 kilometres, depending on the region (Figure 4).

The hydraulic permeability of crystalline rock decreases with increasing depth, and therefore in order to be able to circulate fluids in the geothermal reservoir, permeability must be artificially enhanced. The deeper heat is to be sourced, the more challenging it is to enhance permeability. While shallow boreholes are less expensive to produce than deep ones, their operation must be enhanced with a heat pump. It is possible to drill individual boreholes thousands of metres deep that operate on the same principle as shallow ground source heat wells. Such boreholes can be completely or only partially cased, and the deeper the well is, the more heat it can collect. A borehole that is open at bottom can utilise natural water-conducting structures in the bedrock, in which case the risks involved are the same as with other systems that circulate water in the bedrock (Section 4.1). (Doelling and Schulte 2010; Raymond et al. 2015.)

3.3 Enhanced geothermal heat production, or EGS

Enhanced geothermal system (EGS) plants can be built in areas where the natural hydraulic permeability of the Earth crust is normally too low for circulating water. Hydraulic permeability is enhanced by injecting large amounts of water into the borehole, with the aim of expanding the fractures present in the rock. This is called hydraulic stimulation. Stimulation induces seismicity, but it is an essential part of building an EGS heating plant. The mechanisms of hydraulic stimulation are explained in Section 4.1. The fractures present in the bedrock can also be stimulated chemically by dissolving the secondary minerals with acid.

In EGS, the borehole is cased down to the desired depth, and the last 500–1,000 metres, i.e. the part where the water is to circulate from the injection borehole into the production borehole, is left open (Figure 5). After this the borehole is stimulated with over-pressured water. The flow routes of water, the structures with the greatest permeability, can be traced by locating earthquakes induced by the flow of water. The direction in which the rock fractures depends on the ambient stress conditions (Majer et al. 2007). Once the direction in which the majority of the fractures have propagated is determined, the drilling of the second targeted borehole may commence.

One of the most important factors in EGS is to ensure that the network of fractures (the geothermal reservoir) is of a suitable size and that the rate at which water flows through it remains as consistent as possible. Potential problems include the opening of one or more large flow routes, which can cause water to flow to the production borehole before it heats up to a sufficient degree. Another potential

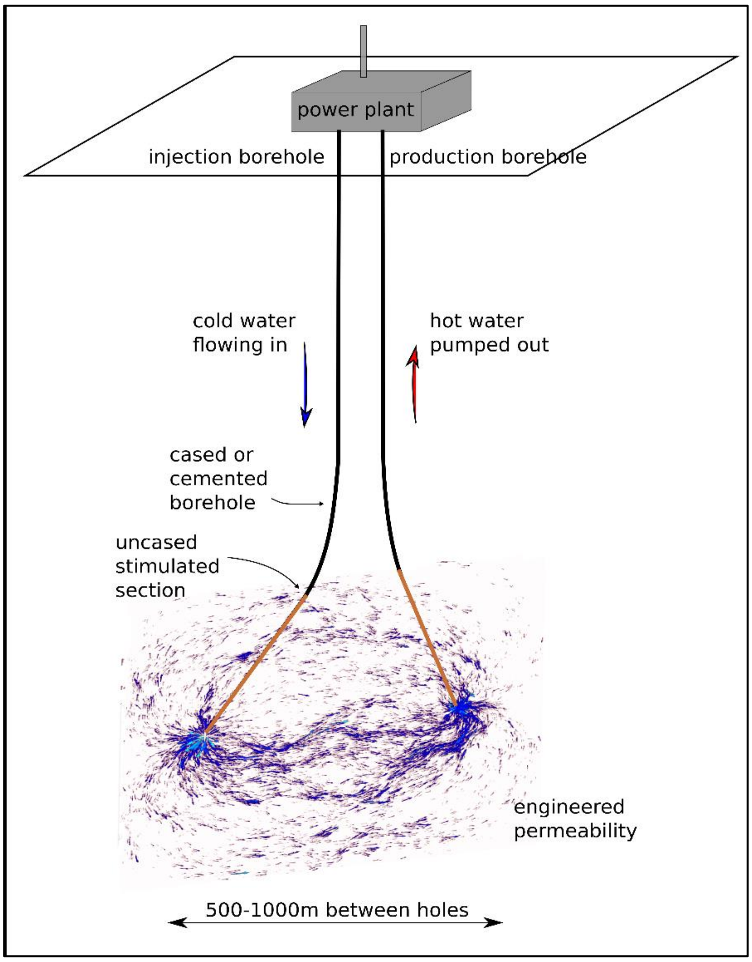

Figure 5: The concept of an enhanced geothermal system.

problem is water flowing into small fractures away from the production borehole, in which case the water cannot be extracted via the production borehole and simply remains in the bedrock.

The circulation of water between the two boreholes is faster than the heat transfer in the surrounding rock and it cools down the reservoir. Thus, EGS has a finite production life, after which the water will not heat up sufficiently as it travels between the injection borehole and the production borehole. The service life depends on the temperature and thermal characteristics of the rock, the structure of the geothermal reservoir and the flow rate of the water.

While there are EGS plants in operation around the world, the majority of them are built on sedimentary formations or near the ground surface, where the permeability of the bedrock is higher by several orders of magnitude than in crystalline rock. The number of sites where the geological conditions are comparable to those in Finland is low. Reaching the required 100°C temperature in Finland's cool bedrock requires drilling boreholes down to depths over 5 kilometres. EGS heating plants can also be based on shallower boreholes (e.g. 2–3 km), and the required temperature is reached with a heat pump. Table 1 provides examples and parameters of EGS plants built on crystalline bedrock.

- Soultz-sous-Forêts is located in the eastern part of France, in the Upper Rhine Plain. The bedrock there is composed of granite below an approximately 1.4-kilometre thick layer of sedimentary formations. Launched in 1987, the Soultz geothermal plant project was the first EGS research project conducted in Europe. At present (2019), the power plant generates heat and electricity. (Evans et al. 2012; Feder 2018.)

- The Basel geothermal plant in Switzerland, in the southern end of the Upper Rhine Plain, is a project that was put on hold in 2006 due to a large induced earthquake. The earthquake occurred after fluid injection had been halted due to elevated seismic activity. The local population initially had a very low tolerance for induced earthquakes, as the city was badly damaged in an M 6.7 earthquake in 1356. The induced earthquakes cost the company a total of 7 million Swiss francs in damages, and the seismic risk in the area has remained elevated for years following the decommissioning of the plant. (Majer et al. 2007; Häring et al. 2008.)

- The Landau geothermal plant in Germany is also located in the Upper Rhine Plain, near Soultz. The two largest earthquakes recorded in the area (M 2.7 and M 2.4) occurred during the power plant's maintenance break in 2009. The area has also experienced considerable isostatic uplift. The plant is still operational and generates both heat and electricity. (Hagag and Obermeyer 2017.)

- The Cooper Basin geothermal plant was located inland in the eastern part of Australia. The local bedrock consisted of granite under a 3.6-kilometre thick layer of sedimentary rocks, so the boreholes were drilled only 700 metres down into the granite. Since the plant was located far away from inhabited areas, the earthquakes induced by fracturing did not cause as much concern as in densely populated Europe. The geothermal plant failed to reach its target output of 50 MW and was decommissioned in 2016. (Asanuma et al. 2004; Hogarth and Holl 2017; Feder 2018.)

- The construction of the Pohang geothermal plant located in South Korea began in 2012. During the stimulations conducted in 2016–17, the magnitude of the largest induced earthquake was M 3.2. In November 2017, two months after stimulation had ended, the area suffered an M 5.4 earthquake. This earthquake injured 135 people, caused structural damage to 57,000 sites and had a total cost of over 300 million US dollars. A recently published report on the event prepared by the South Korean government confirmed the link between EGS operations and the earthquake. As such, the earthquake is the largest and most destructive earthquake induced by an EGS project so far. (Grigoli et al. 2018; Kim et al. 2018; Korean Government Commission 2019.)

Table 1. Examples of EGS geothermal plants around the world and their key parameters: borehole depth, distance between the injection and production boreholes, target temperature, total volume of water injected during stimulation, maximum flow rate, thermal power capacity and the magnitude of the largest induced earthquake (M_{max}).

Geothermal plant *status*	**Depth (km), distance between boreholes (m)**	**Temperature (° C)**	**Injection volume (m^3)**	**Max flow rate (l/s)**	**Power produced**	**M_{max}**
Soultz-sous-Forêts *in operation*	5 650	200	39,800	90	30 MW heat 3 MWe electricity	2.9 after stimulation
Basel *on hold*	5	190	11,500	55		3.4 during stimulation
Landau *in operation*	3 1,500	160		80	3 MW heat 3.8 MWe electricity	2.7 during production stoppage
Cooper Basin *decommissioned*	4.3 700	260	2,500	25	1 MW heat	3.7 during stimulation
Pohang *on hold*	4.3 600	140	12,800	48		5.4 after stimulation
Otaniemi *under construction*	6.4	100	18,160	30		1.8 during stimulation

3.4. Geothermal projects in Finland (2019)

In Finland, permits have so far been applied for the establishment of two geothermal heating plants. One of these is under construction in Otaniemi, Espoo (two boreholes with a depth of approximately 7 km), while the other is planned in Tampere (a single borehole with a depth of approximately 8 km). Both permit applications have been based on the Land Use and Building Act and they have been submitted to the city’s building control department. Based on these applications, the City of Espoo issued an expanded action permit on 20 August 2015 and the City of Tampere issued a building permit on 16 September 2015.

In Espoo, the action has been linked to the drilling of a ground source heat well in accordance with Section 62 of the Land Use and Building Decree (895/1999), which has since been overturned. Nowadays the drilling of a ground source heat well intended for the utilisation of geothermal heat is considered to be subject to an action permit in accordance with Section 126a(12) of the Land Use and

Building Act, meaning that a permit applicant can apply for an action permit instead of a building permit. Regarding ground source heat wells, the Act clarifies that an action permit is not required if the action is based on a legally binding land use plan. Furthermore, a local municipal administration may stipulate in its building ordinance that an action permit is not required for actions that can be considered minor. The Land Use and Building Act does not include any specifications on the depth of ground source heat wells.

In the cases of both the Espoo and Tampere permit applications, statements were requested from the relevant ELY Centre (Uusimaa and Pirkanmaa). In addition to this, in Espoo the City's Environment Centre was also asked to comment on the application. In its statement, the Pirkanmaa ELY Centre commented that, based on the information provided, the deep hole drilling is not subject to permits based on the Environmental Protection Act or Water Act (587/2011) or to the environmental impact assessment procedure, based on the Act on Environmental Impact Procedure. However, the Pirkanmaa ELY Centre stated that the action may become subject to an environmental permit due to noise or dust nuisances affecting adjoining properties, based on Section 27(3) of the Environmental Protection Act and Section 17(1) of the Adjoining Properties Act, for example. The hearing of neighbours in accordance with Section 133 of the Land Use and Building Act was taken into account in both the Espoo and Tampere permits. In its statement, the Pirkanmaa ELY Centre also considered the location of the site in relation to groundwater areas and stated that the project is not located in a groundwater area.

Lessons learned from the first stimulation phase of the Otaniemi heating plant in Espoo are detailed in Section 4.4.2.

4. Seismic risk management of deep geothermal plants

The injection of water into the bedrock alters the ambient stress condition, which may cause earthquakes. Earthquakes caused by human activity are called induced earthquakes. Besides geothermal operations, they can be caused by oil and gas production, underground mining, water masses near large reservoirs and wastewater pumping. The risk of induced seismicity is controlled by examining which factors affect it and by monitoring operations that induce seismicity. This section serves as background information for the recommendations concerning the permit applications of geothermal power plants (Section 5). The section describes the mechanisms of induced earthquakes, the surveying of permitted ground motions, the determination of seismic hazard and risk and the principles of seismic monitoring.

4.1 Induced seismicity

An induced earthquake, i.e. an earthquake caused by human activity, does not significantly differ in mechanism from a natural earthquake. A natural, or tectonic, earthquake occurs when the strain built up in the Earth's crust at some point exceeds the strength of the rock material, causing the strain energy to release in the form of ground motion. Crystalline rock contains plenty of fractures and faults of different sizes, which form weakness points in the rock. At any given moment, some of these faults are in a state of critical stress, which means that even the slightest change in the state of stress is enough to trigger an earthquake (Zoback et al. 2002; Gischig and Preisig 2015). Natural causes for the accumulation of stress include the movement of tectonic plates and postglacial rebound. An induced earthquake is triggered if the change in stress caused by human operations is large enough for rupture-initiation, in critical or non-critical state.

In EGS projects, the natural permeability of rock is enhanced via the injection of water into the rock at high pressure. This fractures the bedrock in two distinct mechanisms. The first mechanisms, hydraulic fracturing (Figure 6a), requires a pressure increase that is large enough to exceed the minimum principal stress ($\sigma 3$). This opens tensile fractures in the rock, which first extend perpendicular to the walls of the fracture and $\sigma 3$ and then propagate in the direction parallel to the fracture walls. The injected water can

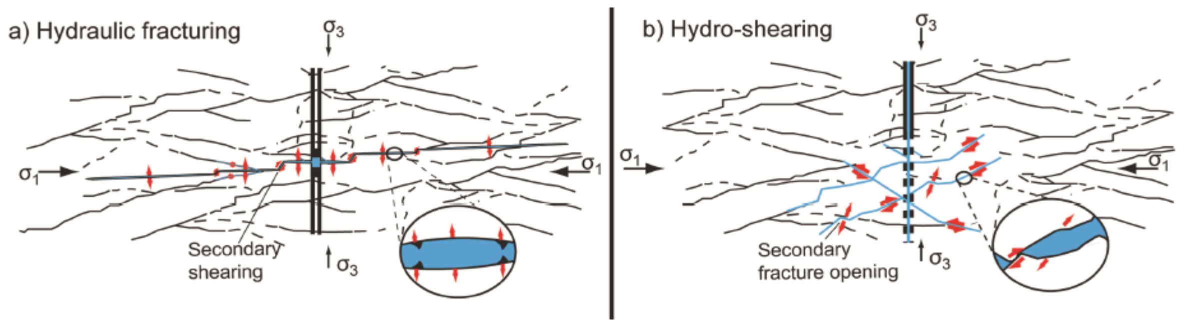

Figure 6: The mechanisms of hydraulic stimulation: a. hydraulic fracturing, tensile fractures, b. hydro-shearing, motion along the favourably oriented fractures. σ1 and σ3 are the rock's maximum and minimum principal stress. Adapted from: Gischig and Preisig (2015, Fig. 1).

also include grains of sand or equivalent synthetic compounds that prevent the tensile fractures from closing once the high-pressure injection ends. This mechanism can also create fractures in intact rock. Hydraulic fractures grow slowly, reaching lengths of no more than a few hundred metres. The process is estimated to release such a low level of seismic energy that it does not affect the area's seismic hazard. (Foxall et al. 2015.)

The second mechanism, hydro-shearing (Figure 6b), requires the pressure of the injected water to overcome the frictional resistance of pre-existing, favourably oriented fractures in the bedrock. This causes the different sides of the fracture to slip in relation to one another. The resulting change is permanent, as uneven surfaces prevent the fractures from closing (Kraft et al. 2009; Gischig and Preisig 2015). This shear slip can follow the formation of tensile fractures, as hydraulic stimulation changes the overall stress state. Shear slips are more difficult to control via water injection parameters, and they are estimated to have caused the largest induced earthquakes (Gischig and Preisig 2015).

The primary mechanisms that induce seismicity in the different operational phases of a geothermal plant are:

- **Pressure changes:** The pores present in rock are filled with water, which causes a certain amount of pressure. When fluid is injected into the bedrock, its state of stress changes and fractures may open up in accordance with Figure 6. Conversely, if the amount of water pumped out of the rock is greater than the amount of water injected, the pressure drops and seismic activity decreases. In highly porous rock, reducing the pore pressure may cause land subsidence. This phenomenon only occurs at geothermal plants where the reservoir is near the surface and where the water extracted from it is not injected back into the reservoir.
- **Earthquake interactions:** The energy released in an earthquake may trigger additional earthquakes. Especially if there are critically stressed fault zones nearby, which only require a small stress change in order to slip.
- **Chemical changes:** Different minerals react differently with injected water, causing chemical changes in the rock, such as clay formation, mineral crystallisation and the weakening of bonds in fractures, which further changes the frictional resistance of fracture surfaces. All of these changes occur in existing fractures, i.e. weakness points of the rock. When these fractures slip, earthquakes are induced.
- **Temperature changes:** In the production phase, the rock gradually cools down, and the resulting contraction may open new fracture surfaces along which water can propagate. The increase in permeability and the changes in flow rate and pressure may induce seismicity further away from the borehole. Temperature stabilisation takes at least as long as the action that changed the temperature of the rock. In the drilling phase, the rock warms up and the resulting

thermal expansion increases stress. This temperature-induced change in pressure is so minor that it does not usually induce seismicity.

The effects of water injection can be roughly estimated in advance based on the geology of the area and the operational parameters of the geothermal plant. However, there is little observational data available on induced seismicity. Many estimates are based on theoretical models and may change as a result of further research:

- **Bedrock type**: Crystalline rock is typically more susceptible to earthquakes than sedimentary rock (Evans et al. 2012). Information on rock types and their characteristics is also important in regard to drilling and is obtained from rock cuttings recovered during drilling.
- **Faults in the area:** Water injection in the vicinity of active faults clearly increases the probability of induced earthquakes (Wiemer et al. 2017), as a result of which EGS projects should generally avoid extensive, seismically active fault zones. The activation of faults is dependent on their deep structure and orientation in relation to the ambient stress field. Information on the deep structure and slip tendency of faults is obtained via stress field and gravity measurements and by comparing the orientation and mechanical properties of faults to the local stress field, for example.
- **Fault zone size:** The size of an earthquake depends on, how large an area of a fault is activated at once and on how large the fault movement is. Larger continuous faults have greater potential for large earthquakes. A large earthquake may cause more damage, as the fault movement is greater, persists longer and releases more energy. Information on bedrock units and the size of faults is obtained via site-specific geophysical surveys and modelling.
- **Injected fluid quantity**: The greater the volume of bedrock subjected to stress changes, the greater the expected number of induced earthquakes (Section 4.3.2).
- **Pore pressure:** The pore pressure of rock is often near critical, due to which even the slightest of changes may trigger an earthquake. The more rapid the change, the greater the probability of seismic events (Majer et al. 2007).
- **Heat reserve depth:** Based on the strength profile of the Earth's crust, it has been estimated that changes in the stress field deep in the bedrock may induce larger earthquakes (Gischig and Wiemer 2013). The crustal stress increases consistently down to a depth of approximately 10–15 kilometres, and a deep fault movement can thus release more energy than a fault movement that occurs close to the surface. This depth correlation is based on theoretical modelling, but there is little empirical evidence to support it (Wiemer et al. 2017).
- **Background seismicity:** It has been proposed that areas with low background seismicity would not be susceptible to large induced earthquakes (Evans et al. 2012). According to more extensive studies, there is no correlation between the magnitude of induced or natural earthquakes and an

area’s background seismicity (Wiemer et al. 2015). However, background seismicity should still be determined as part of natural hazard assessment (Section 4.3.1).

Induced seismicity is primarily focused to a radius of approximately 500 metres from the injection borehole, but fluid injection is known to have also triggered earthquakes further away from the borehole (Goebel and Brodsky 2018). Confirming that such earthquakes were caused by human activity is difficult, because they usually occur in faults that were already prone to slipping in the local stress field.

In operations that induce earthquakes, it is important to be able to objectively and transparently separate induced earthquakes from other seismic activity (explosions, natural earthquakes). The public attitude towards induced and natural earthquakes is different. People are generally less tolerant of the former, and even a minor seismic observation may cause those who find damage in their buildings to demand compensation regardless of whether the damage was caused by an observed event or something else. Nowadays there are effective methods available for differentiating explosions from earthquakes, based on spectrum analysis, for example Kortström et al. (2016). Induced and natural earthquakes can be differentiated with the help of fault plane or moment tensor solutions. The solutions provide an assessment of the fault movement occurring at the earthquake source and the causative stress field. A moment tensor solution provides the most accurate description of the source mechanism of the earthquake, as it models not only the movement of the fault, but also factors such as the role of volume change in the origin of the earthquake (Foulger and Julian 2015). Both methods require the presence of a sufficiently dense seismic monitoring network around the plant (section 4.4).

The environmental impacts of an earthquake depend not only on its size, but also on its depth and location. Earthquakes that occurs close to the surface are more destructive than deep earthquakes of the same size. Moreover, even large earthquakes may go unnoticed if they occur in the middle of a desert, whereas in densely populated areas relatively small earthquakes may cause considerable destruction. In populated areas, people may sense very small earthquakes and find them disruptive. As such, the assessment of the risks of induced seismicity should ideally take into consideration not only the magnitude of earthquakes, but their peak ground velocity and acceleration (PGV/PGA, Section 4.2) as well. This is because PGV and PGA describe ground motion at the point of measurement, whereas magnitude describes ground motion at the earthquake source. The impact of an earthquake of a specific size at the surface depends on the depth and distance of the event and on the geology of the area. The vibration resistance of many structures and devices is also defined in terms of velocity and acceleration. The seismic risk assessment that is conducted prior to every stimulation project includes a prediction model for the greatest ground motions. These prediction models can be updated during and after water injection based on data collected about the ground motions caused by induced seismicity and the impacts thereof. (Bommer 2017.)

Since enhanced geothermal systems inevitably induce seismicity, the locations of EGS plants should be optimised so as to minimise the harmful impacts of seismicity and ensure that the distance between the plants and the sites that they heat does not result in significant heat loss. The appropriate distance must be determined on a case-by-case basis, as it depends on the size and activity of local faults. Due to the mechanical properties of rock, the largest induced earthquakes are centred around the outer edges of the stimulated area (the so-called Kaiser effect), and the risk persists until the induced stress fades, which may take up to several years (Baisch and Harjes 2003, Zang et al. 2014).

4.2 Permitted ground motions

The impacts of the ground motions caused by earthquakes and explosions on people and structures are usually assessed with the help of peak ground acceleration (PGA) or peak ground velocity (PGV) values. PGV limits are more commonly used in construction work and related planning. Figure 7 illustrates the potential impacts of different peak ground velocities on people and buildings. The human threshold of perception can be as low as 0.05 mm/s (RIL 253-2010), and according to Bommer (2017), the lowest PGV that can cause minor damage to weak structures is 15 mm/s (these limits are not exact).

Table 2 lists the PGV limits for blasting work in different soil types provided in the guidelines published by the Finnish Association of Civil Engineers (RIL 253-2010). The table was originally prepared for excavation blasting, which is why the values provided in it are not directly applicable to the monitoring of ground motions caused by earthquakes. Blasting is always carried out according to a pre-defined schedule, whereas induced earthquakes may occur at any time. Furthermore, the seismic waves produced by explosions travel in the fragmented surface part of the Earth’s crust, where seismic energy fades rapidly with distance. Conversely, the seismic waves caused by earthquakes travel deeper inside

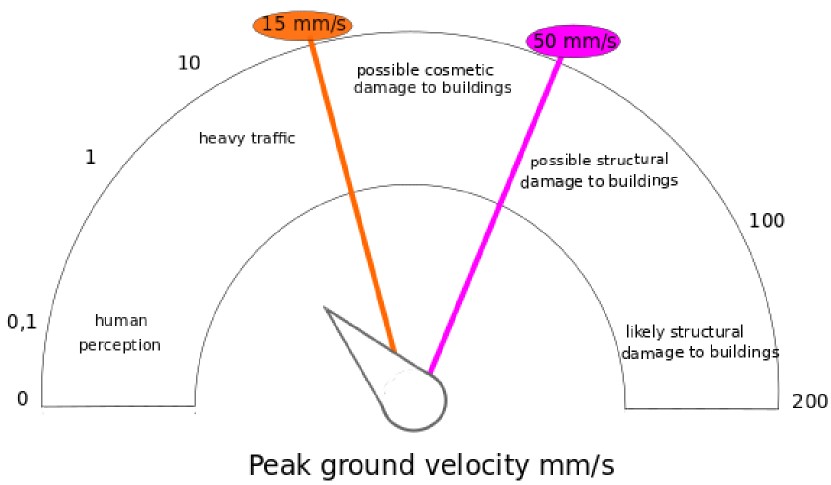

Figure 7: Examples of the impact of ground motion on people and structures. Adapted from: Bommer (2017) and RIL 253-2010.

the crust, and attenuate slower due to propagating mostly in solid, crystalline rock. There are also differences between the energy and frequency content of explosions and earthquakes: An explosion radiates seismic energy evenly in all directions, whereas the radiation pattern of an earthquake depends on factors such as the geometry of the fault and the direction of movement on the fault plane. An earthquake also has a wider frequency spectrum than an explosion (Kortström et al. 2016).

Table 2: Peak ground velocity limits (PGV, mm/s) for different structure classes on different types of soil and bedrock for measurements conducted at distances of 1 m and 2,000 m (in parentheses) from the blasting site according to the guidelines published by the Finnish Association of Civil Engineers (RIL 253-2010 vibrations caused by construction). The values provided in the table are not directly applicable to deep hole drilling.

Structure classes:	**Soil type:**			**Solid rock**
	Soft clay	**Silt, sand**	**Moraine, gravel**	
Heavy reinforced concrete and steel structures, bridges, piers, etc.	15.75 (5.25)	31.5 (8.75)	61.25 (12.25)	245.00 (15.75)
Steel and concrete structures, industrial	11.25 (3.75)	22.5 (6.25)	43.75 (8.75)	175.00 (11.25)
Steel and concrete structures, residential	9.00 (3.00)	18 (5.00)	35 (7.00)	140.00 (9.00)
Brick structures and similar	7.65 (2.55)	15.3 (4.25)	29.75 (5.95)	119.00 (7.65)
Light-structured and vibration sensitive buildings	4.95 (1.65)	9.9 (2.75)	19.25 (3.85)	77.00 (4.95)

When the soil around a planned plant site is surveyed, any thick, soft occurrences of loose soil (including clay soil) are also categorised as potentially vibration sensitive areas. The seismic waves caused by an earthquake slow down and are also amplified as they pass from crystalline rock into the soft layer of

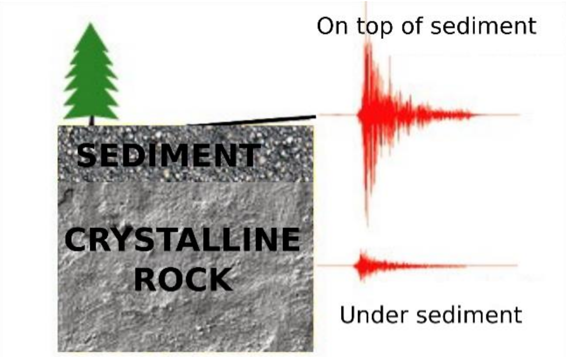

Figure 8: Amplification: the soft surface layer amplifies ground motion. Adapted from https://pubs.usgs.gov/fs/fs-131-02/fs-131-02-p4.html.

soil near the surface of the ground (Figure 8). The waves can be even further amplified by the shape of the ground surface. This occurs, for example, in sediment pools, where the seismic wave is amplified as it is repeatedly reflected from the edges and surface of the structure.

Seismic hazard maps are often based on PGA values, which are reported as percentages of gravitational acceleration g (9.81 m/s^2). According to EU standards (EN 1998:1 2004), earthquakes do not need to be taken into account in areas where PGA is estimated to be lower than 0.04g (=0.39 m/s^2). In Finland, PGA is approximately 0.02-0.03g (Figure 9), and thus earthquake loads are not taken into consideration in the construction planning of conventional buildings. Special sites with sensitive infrastructure, with special regulations and limits are at high risk of damage. In such cases special guidelines on greatest permitted vibration velocities are followed and vibration dampeners scaled according to the environment are used. If the level of seismicity changes, the scaling and dampeners may have to be readjusted.

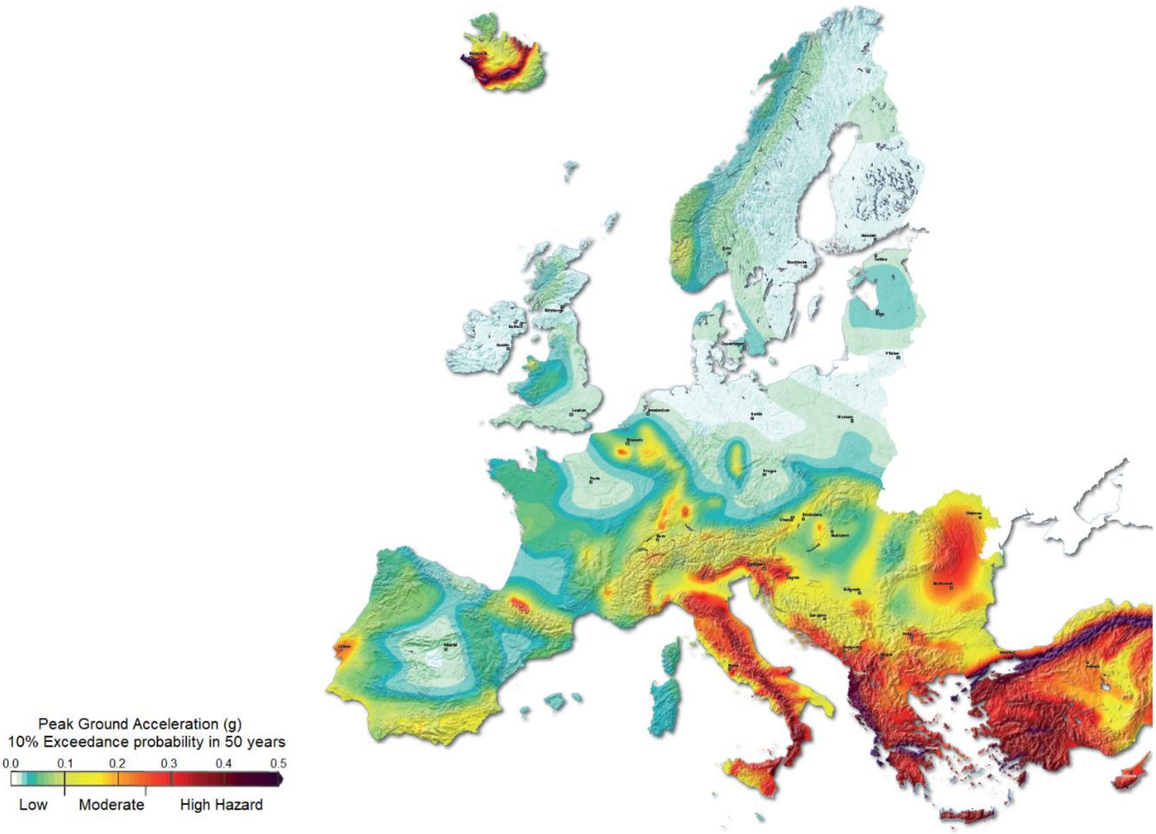

Figure 9: Natural seismic hazard in Europe as PGA values. The colour scale denotes the PGA value (g) that is exceeded once every 500 years on average. Finland is a low hazard area. Source: Giardini et al. (2013).

4.3 Determining seismic hazard and seismic risk assessment

Seismic hazard means the probability that a given earthquake magnitude or some other ground motion parameter will be exceeded in a given area within a specific window of time. Seismic hazard is defined statistically (probabilistic seismic hazard analysis, PSHA) and/or based on the source parameters of the area (deterministic seismic hazard analysis, DSHA). In the case of geothermal plants, seismic hazard assessment consists of two parts: natural and induced. The natural seismic hazard of the area serves as the basis for determining the induced seismic hazard caused by the seismicity induced by water injection.

The steps of the hazard assessment procedure are: a) the determination of the area's background seismicity, b) the surveying of faults and local geology, c) the preparation of a model for predicting ground motion and d) estimating the activity of faults, the frequency of earthquakes at different magnitudes and the maximum magnitude of earthquakes. In the induced seismicity hazard assessment the operating parameters of the plant (including water injection volume and pressure) are included. The assessment is difficult, as the amount of accumulated empirical data about the subject is low (Majer et al. 2012).

Seismic risk analysis estimates the damage and costs that an earthquake could potentially cause in the target area. The risk analysis uses the results of the hazard analysis as input data. It also takes into account the amplifying effect of the soil, the buildings and people exposed to earthquakes and the secondary hazards resulting from earthquakes, such as landslides and tsunamis (Bormann 2002, Wiemer 2017). Examples of approaches and methods that can be used to calculate the hazard and risk of induced seismicity can be found in the publications of Bommer et al. (2015) and Walters (2015), among others. There are also various risk analysis tools that have been developed for seismic risk assessment, such as GRID (Trutnevyte and Wiemer 2017) and SELENA (SELENA 2018).

4.3.1 Surveying background seismicity and natural seismic hazard

Determining the level of background seismicity in a given area requires access to an earthquake catalogue that covers the seismic history of the area as comprehensively as possible. The key parameters of this catalogue are the time and date, location, depth and size (intensity, magnitude) of each earthquake. The catalogue is homogenised so that the sizes of earthquakes that occurred at different times are comparable. The statistical methods used in hazard analysis presume that earthquakes are independent of one another. Because of this, the catalogue must be purged of any earthquakes caused by human activity and any after- and foreshocks associated with major events.

The resulting earthquake data are used to calculate the frequency and maximum magnitude of events and the probability of exceeding a specific magnitude within a given time window in the studied area (Kijko and Sellevoll 1989, 1992; Kijko 2004; Kijko and Singh 2011; Kaisko 2018). The estimate of the maximum magnitude can also be deterministic, in which case it is determined based on the empirical relationships between the fault's length, area and maximum and average displacement.

The EVOGY project, which ended in January 2019, involved the creation of a new equation for predicting ground motion in Fennoscandia and comparing it to older ground motion prediction equations (Fülöp et al. 2019). The equation can be utilised in the creation of a hazard map of the area of Finland.

4.3.2 Induced seismicity hazard

The maximum magnitude of earthquakes induced by water injection has been found to correlate with the volume of water injected, and thus the maximum magnitude might be predicted by modelling. The input parameters are the volume of water injected and the characteristics of the heat reserve, such as size or hydraulic diffusivity (how quickly water passes through a porous volume). Many models also make use of statistical parameters derived from background seismicity. Figure 10 illustrates a simple model (McGarr 2014), in which the earthquake magnitude depends on the volume of water injected and the characteristics of the rock reservoir. The figure shows that the size of seismic events has increased as the volume of water injected increased. (Shapiro et al. 2007, 2010; McGarr 2014; Van der Elst et al. 2016)

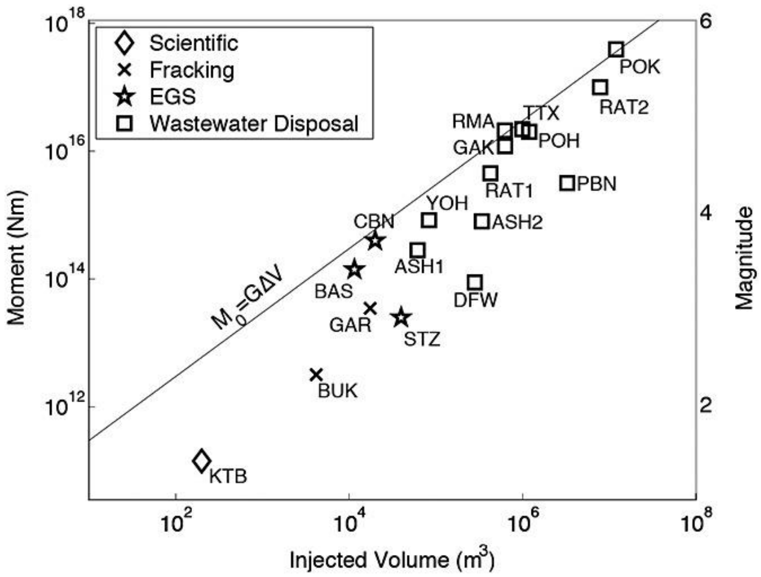

Figure 10: A correlation between water injection volume and earthquake seismic moment/magnitude at different sites. The line is the theoretical upper moment limit. Source: McGarr (2014, Fig. 2).

Figure 11 shows a comparison between the maximum magnitude of earthquakes induced by water injection at the Otaniemi heating plant and the maximum magnitudes predicted by three different models (McGarr 2014; Van der Elst et al. 2016; Galis et al. 2017). In the case of Otaniemi, all three models predicted a higher than realised maximum magnitude based on the volume of water injected (St1 2018b; Saarno 2018). On the other hand, the magnitude of the Pohang earthquake (see Table 1) clearly exceeds the theoretical upper limit shown in Figure 10.

None of the aforementioned models take into account all the necessary parameters, and thus they are only approximate. The seismic hazard assessment for induced seismicity should be based on the site

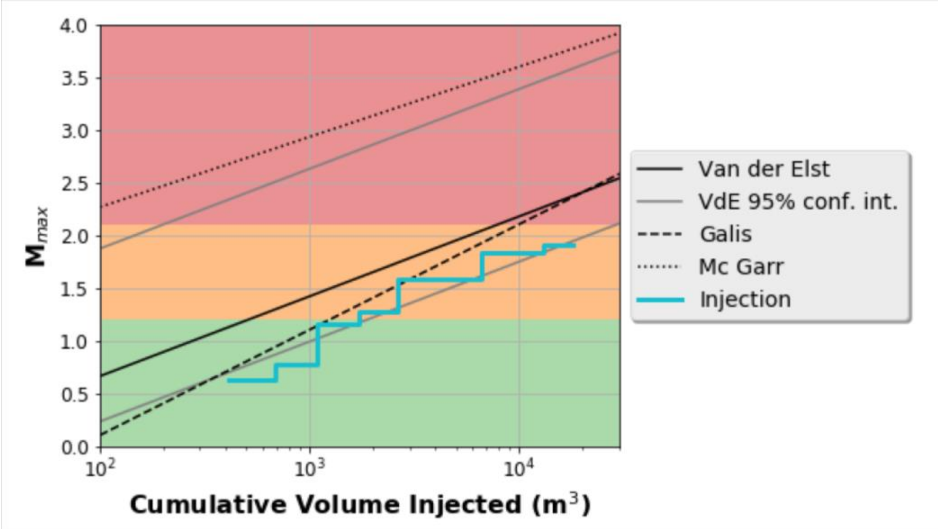

Figure 11: Correlation between water injection volume and maximum magnitude at Otaniemi (in blue) compared to three different prediction models: McGarr (2014), Van der Elst (2016) and Galis (2017). The Van der Elst model's 95% confidence intervals are depicted in grey. Source: St1, (2018b).

specific data and the best suitable physical and statistical models. Both data and models are to be updated during the operation.

4.4 Seismic monitoring system

The aim of the seismic monitoring during the operation of a geothermal plant is to detect and locate seismic events that may cause damage in the vicinity of the plant. The monitoring is tuned to differentiate induced earthquakes from other seismic events and to monitor the development of the seismic activity and its potential to shift from the operating area to the surrounding bedrock (Majer et al. 2007; Ungemach and Antics 2015). Induced seismicity is monitored with the help of a dense seismic network connected to a real-time seismic analysis system. The plant operator is responsible for the implementation of the seismic monitoring system.

Seismic events are recorded by instruments that measure ground motion in three mutually perpendicular directions (vertical, east-west, and north-south). These instruments include accelerometers, seismometers and geophones. Accelerometers that measure time series of ground motion acceleration are ideal for monitoring ground motion. Seismometers and geophones that produce time series of ground motion velocity are generally used to identify, locate and determine the size of seismic events. A seismic monitoring network of the plant area must be in operation well before the commencement of deep drill hole drilling, because both the testing of the network and the determination of the level of background seismicity requires a monitoring period of 1–6 months. The area's background seismicity serves as a baseline for the seismicity occurring during operations.

The radius of the area to be monitored should be at least twice the radius of the geothermal plant's area of effect, or in some cases even larger. The area of effect should be determined as part of preliminary studies. Fluid injection in boreholes drilled in crystalline bedrock has been found to induce seismicity at horizontal distances of 0.5–2 kilometres from the borehole and depths of approximately ± 1 kilometres from the water injection level. As such, the area to be monitored extends to a distance of at least 4 kilometres from the plant and to a depth of at least one kilometre below the water injection level. (Figure 12)

The configuration of the seismic network depends on the desired location accuracy and threshold magnitude. When monitoring stimulation, the network should be dense enough to detect all seismic events of M > 0 occurring within the monitoring area and to locate them with an accuracy of approximately 200 metres. This accuracy serves to identify induced earthquakes at shallow depths from blasts at surface. In order to locate the deepest induced earthquakes with sufficient accuracy, the radius of the network must be 1–2 times the depth of the monitoring area. For example, if earthquakes at the depth of 8 kilometres is to be located accurately, the radius of the network must be 16 kilometres. A central station of the network should be placed as close to the probable locus of seismicity as possible. It should be equipped with both a seismometer and an accelerometer. If the project involves stimulation, additional accelerometers should be placed at sites with vibration-sensitive equipment (Asanuma et al. 2004; Majer et al. 2007, 2012; Evans et al. 2010; Jung 2013)

Seismic monitoring also involves determining earthquake fault-plane solutions. A practical rule for the accuracy of earthquake fault-plane solutions is that azimuthal gaps, i.e. the empty sectors between the

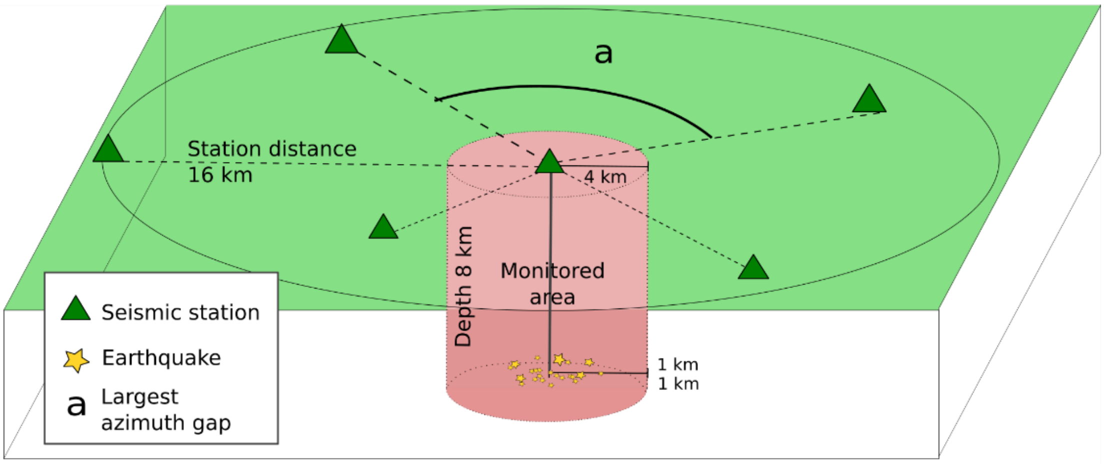

Figure 12: Example of the configuration of the seismic network. The numbers in the figure correspond to the examples provided in the text.

stations detecting the event, should be less than 90 degrees (Figure 12). Theoretically, this is achieved with five stations, provided that they are fully operational. However, the planning of the seismic network must also account for potential malfunctions, and the repair schedules thereof. If the total number of stations is too low, the malfunctioning of even a single station can significantly weaken the network's event location capability. If the minimum station configuration necessary for risk management is not operational, the supervisory party for seismic monitoring can demand temporary halt of the operation of the plant.

In addition to the configuration of the station network, several other factors, such as the noise level of the seismic stations, the location method used and the seismic velocity model of the crust, contributes to the location accuracy of seismic events. Determining the contributing factors is part of the preparation of the station network plan. Seismometers placed in boreholes have a better signal-to-noise ratio than those located at ground level (Plenkers et al. 2015). The use of borehole sensors should be considered in areas with thick layers of loose soil or sediment or in urban areas with high levels of background noise.

The seismic monitoring network should be based on established technology and generally used standards and reference systems, all to be described in the station network plan. The minimum information includes the recording instruments and their metadata, timing and coordinate system and the storage format of digital data.

Risks management of induced seismicity requires real-time monitoring. There are several commercial and non-commercial automated analysis systems, which are optimised for processing seismic signals recorded at close range. However, the automatic event solutions may contain large numbers of errors, which is why the events must be checked and, if necessary, re-analysed manually.

4.4.1 Traffic light system

The operator must implement *a traffic light system (TLS)* which is calibrated to the operating area and which is connected to the automatic analysis system. The system gives out an alert, when the level of seismic activity approaches the threshold value determined as part of the seismic hazard assessment. The TLS sets different location-specific threshold values for earthquake magnitude and peak ground velocity or acceleration, and uses colour scheme similar to traffic lights to indicate whether it is safe to continue operation. As long as the lights are green, operation can continue. A yellow light indicates that a threshold value requiring precautionary measures has been exceeded. At this point procedures in mitigating and reporting of seismic risk enter into effect. If the event in question did not cause any damage and the level of seismicity does not continue to rise, the operations can continue. A red light indicates that a critical threshold value has been exceeded and that operations must be immediately halted in a safe and controlled manner. It is imperative that the event, its immediate impact and the safety measures imposed are reported. The operations cannot continue until authorised by the party supervising the operation. Figure 13 shows the traffic light system used during the first stimulation phase of the Otaniemi heating plant.

In Finland, the magnitude used in a traffic light system must be calibrated to the magnitude used by the Institute of Seismology in the Finnish national seismic network (FNSN).

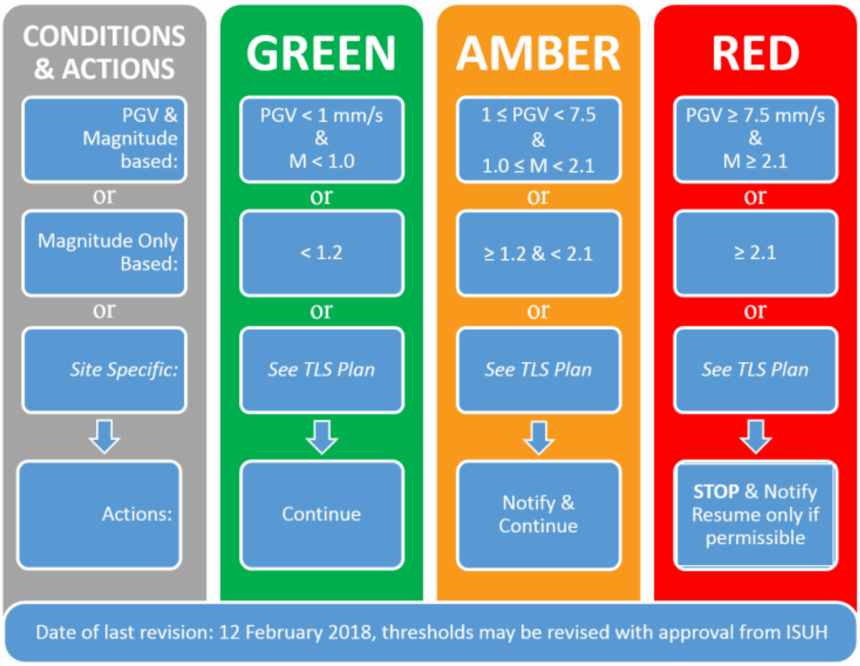

Figure 13: An example of a seismic traffic light system. Source: St1 (2018a).

In addition to magnitude and ground motion, the threshold values used in a traffic light system can also include other variables, such as a rapid increase in the number of minor seismic events. An *adaptive traffic light system* (ATLS) is an improved traffic light system, which – similar to weather forecasts – predicts induced seismicity (Mignan et al. 2018). The input data include site-specific safety norms, real-time water injection parameters and seismicity data.

The threshold values used in a traffic light system are determined based on the seismic response of the area. The values can be updated based on lessons learned during operation. When determining the threshold values, one should remember the so-called nuisance factor. Frequent earthquakes sensed by people may lower their level to react and may reduce the overall acceptability of the project and in the long term may also hinder the launch of similar projects in the future. If the threshold values are set at low enough levels, mitigation measures can be initiated earlier and the probability of potentially damaging events decreases. On the other hand, excessively conservative threshold values reduce the economic profitability of the project.

Measures for mitigating seismic risk include controlling the volume and pressure of injected fluid and the controlled halting of fluid injection. Because fluid injection alters the ambient stress field, the immediate shutdown of fluid injection does not stop seismic activity, but may, instead, even induce it further. There are known examples of EGS projects where the largest induced earthquakes occurred after water injection had already ended (Table 1). A safer method is to decrease the fluid injection pressure gradually, until an acceptable level of seismicity is reached. Instead of providing immediate results, the procedure reduces seismic activity over the long term.

4.4.2 Lessons learned from the stimulation phase of the Otaniemi heating plant project

The stimulation of the Otaniemi project's first borehole was carried out from 4 June to 23 July 2018. During the preceding drilling phase, St1 had established two networks to monitor the seismic activity and ground motion caused by operations. The first network, the *surface network,* consisted of 13 accelerometers placed on the ground surface, of which six were installed at sites containing sensitive measuring equipment, namely at Meilahti Hospital, the University of Helsinki's Accelerator Laboratory, VTT Technical Research Centre of Finland, CSC – IT Center for Science, the Centre for Metrology and Accreditation and St1's office at the drilling site. The second network, the *satellite network,* was intended for the real-time detection as well as location and size determination of seismic events. It consisted of 12 seismometers installed in boreholes at the depths of 300–1200 metres. The Institute of Seismology monitored operations with its own network consisting of permanent seismic stations, five temporary stations and St1's satellite stations.

The drilling of the boreholes did not cause any significant activity compared to the level of background seismicity. During the stimulation phase the Institute of Seismology's automatic location system detected over 5,000 seismic events within a radius of five kilometres from the drill site. All events with a magnitude of M 0 or greater were reviewed and re-analysed manually. Of these events, the number of induced earthquakes was nearly 500. The number of events with a magnitude greater than M 1.0, i.e. events requiring precautionary measures, was 48. St1 reported these events and implemented measures for mitigating seismic risk in accordance with their permit. After the stimulation, the area's seismic activity declined. By the end of 2018, only one earthquake with a magnitude greater than M 1.0 was detected.

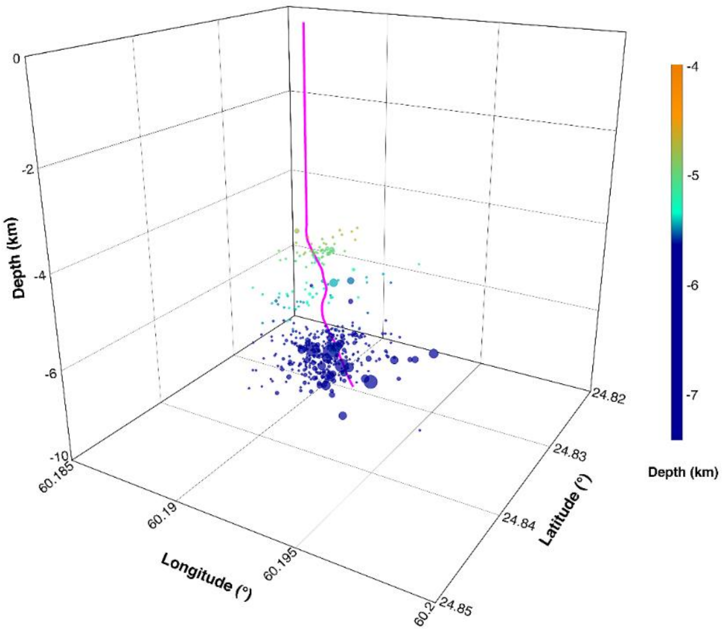

Figure 14: A 3D illustration of the earthquakes detected around the Otaniemi borehole. Earthquakes by the Institute of Seismology and borehole coordinates by St1.

The manually analysed results show that the earthquake sources were located at the depth of 4–6 kilometres and that they were distributed within a distance of approximately 200 metres from the borehole (Figure 14). The highest peak ground velocity of 4.4 mm/s was measured during an M 1.8 earthquake that occurred on 16 July 2018. The peak ground velocity value was well below both the general and the site-specific threshold values (Figure 13). All other peak ground velocities caused by the induced earthquakes were lower than 3 mm/s.

Although the measured ground motion values remained well below the permitted threshold values, the Institute of Seismology received reports of vibrations and sound related to a total of 23 different earthquakes (Appendix 1: Table 3 and Figures 16–17). In general, earthquakes with a magnitude greater than M 1.5, which occur in densely populated areas in Finland, are widely reported. Because the energy of seismic waves attenuates slowly in Finland’s crystalline bedrock, the sounds and vibrations travel longer distances, and they can be felt at considerable distances from the earthquake itself.

Figure 15 shows the observations on the M 1.7 earthquake that occurred on 8 July 2018. The event was felt as far as 10 kilometres from the borehole. The responses are unevenly distributed. There are more observations to the east of the heating plant site than to the west. This may be because an earthquake source radiates energy unevenly in different directions. The distribution of the responses is also affected by population density, building stock and the soil. A thick layer of loose soil or clay under building foundations amplifies seismic waves (section 4.2, Figure 8) and can increase sound and vibration nuisances locally. A large number of the observations also came from buildings constructed on the outcropping bedrock.

In summary, the ground motions caused by the induced earthquakes during the first stimulation phase of the Otaniemi heating plant remained well within the permitted limits. In spite of this, the noise and vibration nuisances caused by the largest (M > 1.5) induced earthquakes were significant, and must be taken into account in future risk analyses.

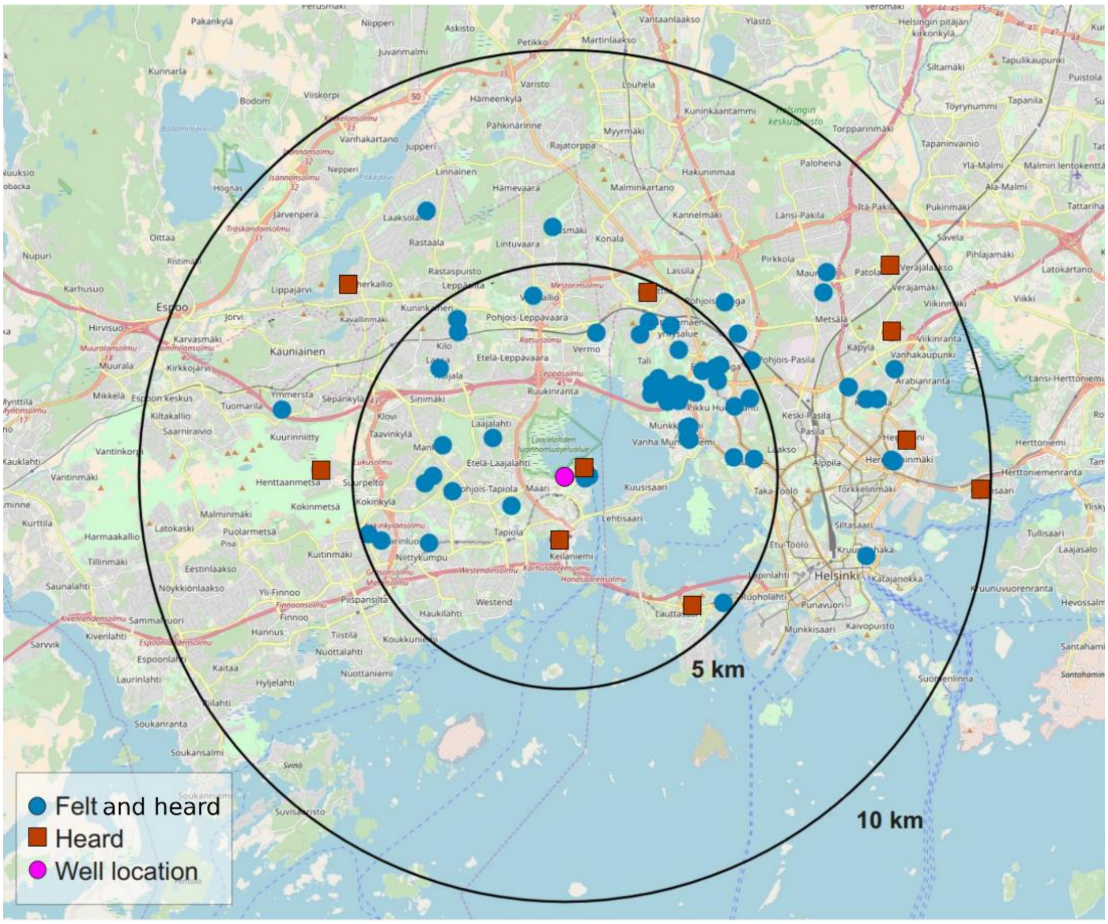

Figure 15: Map of the sound and vibration observations associated with the earthquake (M 1.7) that occurred on 8 July 2018. The circles are drawn at 5 and 10 kilometres radii from the borehole. The blue circles denote sound and vibration observations, while the red circles denote sound observations. The pink circle is the location of the borehole at surface.

5. Recommendations for the permit applications of deep geothermal plants

The permit application for a geothermal plant should support technical and legislative communication related to the plant. The aim is to identify the potential environmental impacts and risks of the plant and present a plausible road map for gaining the acceptance of the local community and the relevant regulatory body. The preparation of a risk assessment is recommended for all deep geothermal plant projects. The risk management procedures of each project should be scaled on a case-by-case basis based on the results of the assessment.

In regard to seismic risk management, the recommendations provided in this report are partly based on the recommendations of the United States Department of Energy and the International Energy Agency (IEA) (Majer et al. 2012) and the Swiss Seismological Service's (SED) 'good practices' in seismic risk management (Wiemer et al. 2017). The recommendations have been adapted to Finnish conditions, based on the Finnish Association of Civil Engineers' guidelines for vibrations caused by construction (RIL 253-2010) and the lessons learned by the Institute of Seismology during St1's first stimulation phase. In regard to other environmental risks, the recommendations are based on the environmental geology expertise and the views of the Geological Survey of Finland.

The permit application for a deep geothermal plant should preferably include descriptions of the following:

1. Background studies
    - Seismic hazard and risk assessment
    - Permissible limits of ground vibration
    - Environmental impact assessment
2. Monitoring and contingency plan
3. Work site plan, description of the drilling technique to be used
4. Communications plan

5.1. Background studies

The purpose of the background studies is to determine whether the chosen location is suitable for the building of a geothermal plant. In the context of a permit application, it is enough to include a review of relevant literature. The assessment should cover the entire estimated area of effect. The assessment involves examining the potential seismic risk and environmental impacts of the plant.
The operator should have comprehensive knowledge of the area's seismic response. The indicators listed in Section 4.1 provide a rough overview of expected seismicity:

- The operating principle of the plant: does the injected water come into contact with rock, and does the construction phase of the power plant involve stimulation. The stimulation and operating parameters: volume, flow rate, pressure and temperature of injected fluid.
- Orientation and magnitude of the stress field in relation to existing faults. Extent and rock mechanical characteristics of the faults.
- Local geology, types of rock and their mechanical properties. Hydrogeological properties, such as the porosity and permeability of the rock, pore pressure and underground water bodies.

When the project progresses, new data are obtained and the assessment should ideally be updated. Borehole measurements are suggested to map the in situ geological, structural geological and physical properties of the bedrock etc., as well as identifying any fracture zones intersecting the borehole.

5.1.1 Assessment of the seismic risk of the area

The recommendations for seismic monitoring depend on whether the heat transfer fluid used by the plant will come into contact with the bedrock or not. The seismic risk caused by a completely enclosed borehole is small. If fluid comes into contact with bedrock, the seismic risk is elevated, and the operations must be more monitored. If the bedrock is stimulated, the seismic risk is even higher, and monitoring must be scaled accordingly. The guidelines provided in this report pertain primarily to a situation, where the construction of the plant involves stimulation or where the used heat transfer fluid comes into contact with the bedrock.

Seismic hazard and risk assessment is described in Section 4.3. One example of applicable risk analysis tools is GRID risk management model (Trutnevyte and Wiemer 2017), which can be applied in the selection of the plant’s location. The model covers seismic hazards, buildings and population that will be exposed, the vulnerability of the area (e.g. local geology, the condition of buildings) and the social reception of the project. Based on the results, geothermal projects can be divided into different risk categories, which are subject to different recommendations concerning monitoring. More information and an example of GRID is provided in Appendix 2. Even if the model is not directly applicable to Finnish conditions, it does, however, provide a good overview of the issues that should be taken into consideration in risk management and it can be used as a basis for a model tailored to Finnish conditions.

5.1.2 Survey on permissible ground vibrations

After preliminary site selection, the next step is to perform a survey on permissible ground vibration levels in the area of effect as regards buildings and the environment and any site-specific planning criteria pertaining to sensitive sites. Sites with sensitive infrastructure include any nearby hospitals and research laboratories. Furthermore, any historically valuable and protected sites must also be taken into account. The permit application should specify the area, where effects will be felt, and the threshold values for ground vibration. The survey is conducted based on Section 4.2.

5.1.3 Environmental impact assessment

The environmental risk factors associated with a geothermal plant can be divided into factors associated with the construction phase and factors associated with the production phase. The construction phase includes the drilling and possible stimulation. The drilling phase is part of construction operations that cause changes in the soil and bedrock, while the production phase is part of stable renewable energy production operations. In general, the environmental impacts of the construction phase are greater than those of the actual production phase, although the former is shorter in duration.

At the time of writing this report, the permit procedures of geothermal plants have been carried out based on either an action permit in accordance with Section 126 of the LUBA or a building permit in accordance with Section 125 of the Act. Whether the project site or other factors necessitate an environmental permit in accordance with the Environmental Protection Act and/or an environmental impact assessment in accordance with the Act on Environmental Impact Assessment Procedure should be assessed on a case-by-case basis. According to Section 6 of the Environmental Protection Act, operators shall have sufficient knowledge of their activities' environmental impacts and risks, as well as the management of these impacts and risks, and ways to reduce adverse impacts.

Geothermal energy production facilities are not considered to fall within the purview of the list of projects in Annex 1 of the Act on Environmental Impact Assessment Procedure (252/2017, EIA Act), due to which they are not automatically subject to the environmental impact assessment procedure. If taking into account the combined impacts of different projects, the geothermal energy production is likely to cause environmental impacts, which are comparable in quality or scope to the projects listed in Annex 1 of the Act, then facilities can fall within the purview of the procedure according to Section 3(2) of the EIA Act. But Annex II of the directive on the assessment of the effects of certain public and private projects on the environment (2011/92/EU) mentions operations such as deep geothermal drilling in the context of extractive industry. According to the Directive, the environmental effects of the projects listed in Annex II must be assessed on a case-by-case basis if they are likely to have significant effects on the environment by virtue, inter alia, of their nature, size or location.

Land use

At the time of writing this report, Finland did not have actual legislation about three-dimensional property or on who has ownership and usage rights at depths of several kilometres underground (with the exception of a mining permit for the exploitation of mining minerals in accordance with the Mining Act (621/2011)). The drilling of a geothermal well intended for the utilisation of ground source heat is specified in Section 126 a (12) of the LUBA as an action subject to an action permit.

The building of a geothermal energy production facility should not conflict with a plan approved for the area (regional plan, master plan or local detailed plan). To identify potential risk factors, the land use situation of the area and its surrounding environment should be determined at a sufficient level of accuracy. The plant's potential area of effect should be outlined with a sufficient margin of error, and land use should be examined throughout the entire area of effect. The examination should also take into consideration any underground structures and operations in the surrounding area and any underground plans. Land use plans could also be prepared so as to reserve areas for a geothermal energy production facilities, as is often done nowadays with wind turbines, for example. In this case the building of a production facility could be linked to the land use planning process and associated permit procedures.

Nature sites

A geothermal plant and the building thereof must not endanger the landscape, natural values or cultural heritage of the area or its surroundings. If the area or its surroundings include areas that are notable in the context of nature conservation or areas reserved for recreational use or conservation in the land use plan, an official statement on the realisation of the project must be requested from the local ELY Centre (Section 6 of the Nature Conservation Act (1096/1996)). If the area includes nature sites as defined in the Nature Conservation Act, the operator must determine the potential impacts of both the drilling and actual production phases of the geothermal plant.

Geology

The soil and bedrock conditions of the geothermal plant and its surroundings must be described in sufficient detail. The survey must detail the area's bedrock type and the thickness of surficial deposits, soil type and its geochemical quality. The geological surveys should focus particularly on the geotechnical properties of the surficial deposits (vibration is covered in greater detail in the section Noise and vibration during the building phase). If the subsurface sediments can be suspected of being contaminated due to previous contaminating operations, for example, the contamination of the soil and associated remediation needs must be assessed in accordance with Section 14 of the Environmental Protection Act before the commencement of the drilling project. The bedrock survey must include an assessment of the prevailing rock type (including any changes therein with depth), the fragmentation of the bedrock and potential fracture zones. It is especially important to identify the occurrence of any radioactive minerals in the bedrock (the handling of drilling waste is covered in the section on Drilling waste).

Water

A geothermal plant and the building thereof must not endanger the state of the area's water bodies. The direction of stormwater flow in the area and potential runoff to local water bodies can be assessed based on the topography of the area. If operations could potentially cause the contamination of water bodies, an environmental permit must be applied for them (Section 27 of the Environmental Protection Act).

Groundwater

A geothermal plant and the building thereof must not endanger the quantity and quality of the area's groundwater or natural or built environment sites that are dependent on groundwater (prohibition against groundwater pollution, Section 17 of the EPA). In this context, groundwater refers to both groundwater present in soil and bedrock. If the project is located in a groundwater area, particular attention must be paid to its potential impacts. A site located primarily in a groundwater area is subject to a permit in accordance with Chapter 3, Section 2(1) of the Water Act (587/2011) because the project may alter the quality or quantity of groundwater. The permit application process involves carrying out surveys on the area's hydrogeology, the state of the groundwater, the groundwater table levels, direction of groundwater flow and the retention time between the site and wells or water intakes. Furthermore, the impacts of the construction and operation of the plant on the quality and quantity of groundwater must be assessed and a plan for groundwater protection measures must be prepared. During drilling and operation, care must be taken so that deep, saline bedrock groundwater does not discharge soil aquifers.

Drilling waste

According to Section 5 of the Waste Act (646/2011), a substance or object is not waste, but a by-product, if it results from a production process whose primary aim is not the production of that substance or object. In order to be considered a by-product, the further use of the generated substance must be certain. According to Section 16 of the Waste Decree (179/2012), the holder of construction waste must organise the re-use, recycling or recovery of generated waste. The drilling residue generated during the drilling of an enhanced geothermal plant does not generally fulfil the criteria defined for by-products, due to which it is considered waste. Drilling fluid consists of soil and drilling mud extracted from the ground and bedrock during drilling, the water injected into the borehole and any chemicals added into the water for adjusting fluid viscosity during drilling. The chemicals used are covered in greater detail in the Section on Chemical handling.

The drilling waste generated during the drilling phase and operation of a geothermal plant consists of ground rock extracted from the borehole with drilling mud (the viscous mixture used in drilling). This by-product is usually referred to as cuttings. The chemical composition of cuttings depends on the type of rock being drilled and the chemicals used. According to Section 8 of the Waste Act, the operator in whose production the waste is generated must, insofar as possible, comply with the order of priority, i.e. reduce the quantity and harmfulness of waste generated, prepare the waste for re-use, recycle it, recover the waste in other ways, or, if there are no other options, dispose of the waste. According to Section 12 of the Waste Act, those engaged in production must be aware of waste generated in production, the environmental and human health impacts thereof, and the related waste management, as well as the possibilities of developing production so as to reduce the quantity and harmfulness of waste. The assessment of the type of waste is conducted primarily by the party whose operations generate the waste.

In accordance with the Waste Act, the operator must see to it that drilling waste is appropriately processed. Unprocessed drilling waste must not end up in water bodies or elsewhere in the environment during drilling, storage or transportation. Generated drilling waste must be either appropriately processed on-site or transported elsewhere for processing. The way in which the drilling waste will be disposed of must be determined before drilling commences.

The water used in drilling can be filtered, purified and re-used for drilling on-site. The water used in drilling must not be allowed to enter the environment or the sewer networks as it is. Instead, a separate assessment must be conducted and a plan prepared on the necessary water processing, which is presented in connection with the permit application. The waste generated in the filtering and purification of the water must be processed in a similar manner as actual drilling waste. The quantity of drilling waste to be generated can be evaluated based on the number of boreholes and the diameters and depths thereof.

During the production phase, the boreholes may need to be flushed from time to time. The cuttings generated during the maintenance flushing of boreholes must be processed in the same way as the drilling waste generated during drilling.

Radioactive matter and radiation

Finland’s most common type of rock, granite, contains small amounts of radioactive minerals. These minerals do not cause any danger or hindrance during drilling. However, there have been reports of radioactive minerals concentrating and accumulating in pipelines in granite areas (Cuenot et al. 2015). Circulating fluid with a temperature of approximately 70°C in the bedrock has been found to precipitate sulphates from barite ($BaSO_4$) to celestine ($SrSO_4$) and sulphides as galena (PbS) minerals. Of the aforementioned minerals, sulphides bind primarily radon, sulphates bind radium and galena binds lead. In terms of radiation exposure, it is notable that sulphates bind radium isotopes Ra-226 and Ra-228, of which Ra-226, in particular, is long-lasting. In addition to sulphates, sulphides and other precipitates, geothermal energy production can also involve electro-chemical reactions that can cause substances such as metallic lead to accumulate on pipes and filters, depending on the composition of the water and bedrock. Precipitates and reaction products containing lead may become enriched with naturally occurring radioactive substances Pb-210 and Po-210 (Päivi Kurttio, written communiqué 18 January 2019). The possible occurrence of radioactive minerals must be taken into account, in addition to which sufficient assessments must be conducted on the radioactivity and activity concentrations of drilling waste.

Geothermal energy production with an open system creates various chemical conditions that may, depending on the composition of the water and bedrock, result in the accumulation of precipitates or electrochemical reaction products in pipes, valves, filters or heat exchangers, for example. These materials may contain elevated concentrations of naturally occurring radioactive substances. Because of this, the radiation exposure resulting from geothermal energy production must be assessed. The assessment must also take into account the waste generated during operation. The obligation to assess radiation exposure generally only applies to geothermal energy production with an open system. However, the reference values for natural radiation exposure from work-related exposure or exposure caused by construction products (Ministry of Social Affairs and Health Decree on Ionising Radiation (1044/2018), Sections 23, 24 and 26) apply regardless of the type of system used. The drilling phase and the waste generated during it must also be taken into account (Päivi Kurttio, written communiqué 18 January 2019).

According to Section 22 of the Radiation Act (859/2018), the operator is responsible for the radiation safety of its operations, and this responsibility is non-transferable. Radioactive waste is generally subject to the Radiation Act, as the Waste Act (646/2011) excludes radioactive waste from its scope of application. According to the Radiation Act, radioactive waste means radioactive matter that must be made safe in regard to its radioactivity. However, it has been noted in a government proposal (HE 28/2018) that it would be appropriate to limit the scope of application of the Radiation Act only to waste in which the quantity of radioactive substances is so high that radiation safety necessitates waste management solutions that differ from those applied to other waste. Therefore waste in which the quantity of radioactive substances is lower than the value for exemption defined in Section 85(2) of the Radiation Act can be re-used, recycled, recovered or disposed of in accordance with the Waste Act. Operations involving exposure to natural radiation do not generate radioactive waste in accordance with the Radiation Act (Section 78(3–4) of the Radiation Act and Section 31 of Government Decree 1034/2018). However, according to Section 78(3) of the Radiation Act, this type of waste must be still be appropriately handled with due consideration to radiation protection. Values for exemption or clearance for naturally occurring radioactive substances in solid materials in secular equilibrium with their progeny are provided in the Radiation and Nuclear Safety Authority's (STUK) regulation on values for exemption and clearance (SY/1/2018). Provisions concerning other operations involving exposure to natural radiation are provided in a separate STUK regulation (S/3/2019). Values for clearance are applied to naturally occurring radioactive substances only if they are used as radiation sources (Päivi Kurttio, written communiqué 18 January 2019).

In Section 78(3) of the Radiation Act, the radiation protection of the public and employees is extended to also cover waste that is not considered to be radioactive waste in accordance with the Radiation Act, but in the waste management of which radiation safety should be taken into account. The operator must ensure that radioactive substances do not have negative impacts on health or the environment. The operator is also responsible for the radiation protection of its employees. (STUK 2017.)

Dust

The Adjoining Properties Act (26/1920) states that a property may not be used in a way that causes undue stress to a neighbour or a person living nearby due to environmentally harmful substances, soot, dirt, dust, smells, moisture, noise, vibration, radiation, light, heat or any other effect. Therefore, drilling must be organised in a way that does not release dust into the environment. Additionally, arrangements must be made so that on-site traffic does not increase dust load in the area.

Noise and vibration during construction

The construction, stimulation and production of a geothermal plant generate noise and vibration in the immediate vicinity of the plant. Before the drilling project is started, the level of noise generated during the work must be assessed and drilling conditions must be arranged so that the guideline values provided in the Government Decision on Guideline Values for Noise Levels (993/1992) are not exceeded. If necessary, the operator must make a noise notification concerning the drilling to the municipal environmental protection authority in accordance with Section 118 of the Environmental Protection Act. The vibration caused during drilling may have significant negative impacts on nearby residents, properties or other operations in the area. Vibration surveying and the demarcation of vibration areas are generally used to support the planning of new traffic lanes (Talja and Törnqvist 2014) and can also be used insofar as applicable in the planning of geothermal plant construction projects. It is important to recognise whether the vibration generated during drilling and production could potentially damage buildings or whether the vibration could resonate in structures located within the area of effect in a way that could impact housing comfort. According to Talja and Törnqvist (2014), vibration propagation is highest in soft and water-carrying soils, meaning clay, silt, gyttja and peat. Vibration may also impact the bearing capacity and slope stability of the ground, and can even cause slopes to collapse under certain conditions. For assessing housing comfort, there are guidelines and recommendations in place in regard to measurements and reference values for maximum vibration (Talja 2011). Vibration caused by induced seismicity is covered separately in Section 4.

Transport

The transportation volumes, routes and timings necessitated by the project, as well as spaces for parking, loading, unloading, servicing and washing vehicles, should be determined as part of the work site plan (Section 5.3). Special transport arrangements may be needed especially during drilling arrangements, when machinery is brought to the site. Drilling waste may also need to be transported from the site to be processed and utilised elsewhere. The water content of the drilling waste may be high, and the transportation equipment used must be suitable for transporting this type of waste. Transport arrangements must be planned prior to the start of the project.

Chemical handling

The productivity of a geothermal well can be improved by chemical treatment. The chemical treatment model must always be selected based on the geological properties of the bedrock and groundwater properties at the site. In other words, chemical treatment should not be conducted by simply replicating a treatment used at another site. This is especially true in regard to replicating a treatment intended for a different bedrock area in Finnish conditions. The chemical reactions caused by the chemicals to be used, their end products and their effects on natural conditions should be determined in advance via geochemical surveys.

In the younger formations of Finland's bedrock, such as the Satakunta sandstone and/or the Muhos claystone area, chemical treatment can be used to increase the hydraulic permeability of the rock and/or remove so-called cementing minerals, which hinder the use of geothermal wells. During the drilling phase, chemical compounds are used in the drilling mud to move the cuttings to the surface and clean the borehole. The most common chemical used for this purpose is so-called mud acid, which consists of a diluted mixture of hydrochloric acid (HCl) and hydrofluoric acid (HF). The mixing ratio of the acids depends on the mineralogy of the rock and the permeability of the bedrock (Crowe et al. 1992). Other chemicals that can be used include corrosion inhibitors and acids that prevent the precipitation of iron; these are used to prevent the breakdown and clogging of fluid transfer pipes.

If chemicals are used in drilling or in the production phase, the transport, loading, unloading, use and storage of the chemical must be appropriately arranged, taking into account the nature of the chemical in question (Chemicals Act 599/2013). The labelling, classification, use and packaging of chemicals must be carried out in accordance with the EU's REACH and CLP regulations (Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures). The necessity of permits related to the storage and handling of chemicals depends on the quality and quantity of the chemicals used.

Particular attention should be paid to occupational safety, and relevant ICSC instructions should be followed at all times.

The energy efficiency and climate sustainability of the plant

It is recommended that the permit application include a description of the benefits of the project from an energy production perspective. The carbon dioxide emission savings resulting from the use of geothermal energy can be presented in the permit application separately for each site. It is relevant to identify which traditional form of energy production is being replaced with geothermal energy and by how much CO_2 emissions will be reduced at each site. CO_2 emissions can be calculated according to Motiva guide 12/2012"Instructions for calculating CO_2 emissions in summaries and the CO_2 emissions coefficients to use (in Finnish)”, for example. It is recommended that the amount by which CO_2 emissions are reduced, compared to fossil fuel-based energy production, is monitored and updated throughout the operation of the plant.

Calculations of the geothermal plant’s total carbon footprint can also be conducted and compared to coal-produced district heat and/or bioenergy production. Carbon footprint calculations should be carried out whilst taking into consideration the use of the plant over the planned time period, for example 50 years. This ensures that total carbon footprint calculations also include the maintenance of the plant and related transportation etc. impacts.

5.2 Monitoring and contingency plan

The permit application should include an assessment of the environmental risks associated with operations, how will they be monitored and prepared for, and a contingency plan, i.e. a plan of action for potential emergency situations. The permit application should also include an assessment of the need for other permits on a case-by-case basis. If necessary, a contingency plan covering the drilling, stimulation and actual operation of the plant is prepared in accordance with Section 15 of the EPA. The permit application should include a plan for the seismic monitoring of the plant (see Section 4.4). The following monitoring recommendations apply primarily to EGS projects, but it is recommended that they also be applied to deep drill hole drilling projects that do not involve stimulation. So far no empirical data has been accumulated on the latter projects and the seismic risk thereof in Finnish conditions.

The local permit authorities of the operating area of the plant should preferably appoint an independent party to supervise the seismic monitoring of the project. This supervisory party should be provided with the real-time recordings of the seismic monitoring network, the plant’s operating reports and the results of both automatic and manual analysis. For example, the City of Espoo authorised the Institute of Seismology to supervise the realisation of the Otaniemi Deep Heat project’s traffic light system. Even if the Institute of Seismology is not authorised to serve as the supervisory party, they should be kept informed of the operating phases of the project, as the Institute is tasked with monitoring seismic activity in the area of Finland and is often the first party to be contacted about sound and vibration observations.

The real-time data of at least one of the monitoring stations must be incorporated into the Finnish national seismic network (FNSN) maintained by the Institute of Seismology. This ensures compliance with the International Atomic Energy Agency’s guidelines for the seismic monitoring of nuclear power areas (IAEA, 2010). Furthermore, this enables calibration of the magnitudes of induced earthquakes to the national network’s magnitude scale.

The project’s project manager, the permit authority, the parties responsible for safety, monitoring and communications and the Institute of Seismology should be informed about any instances of the traffic light system's threshold values being exceeded (Section 5.4.). The incident reports prepared by the operator are delivered to the party supervising seismic monitoring and to the Institute of Seismology.

It is also recommended that the project be insured against potential damage caused by the different operating phases of the plant. See guidelines by the International Development Bank.

5.3 Work site plan, description of drilling technique

It is recommended that separate work site plans be prepared for the drilling and stimulation phase and for the actual operational phase of the plant. The work site plans should describe the use of the work area and the functions therein. The use of the work site area must be planned whilst taking into account adjoining properties (Adjoining Properties Act (26/1920)) and work site traffic. The work site plan must be attached to the permit application and comply with potential municipality-specific special requirements regarding the location of the borehole in relation to adjoining properties, for example. The work site planning also includes a separate risk assessment procedure, consisting of the review and identification of risk factors related to occupational safety and the preparation of a plan for their minimisation.

The work site plan should cover the entire lifecycle of the plant and, thus, also describe the use of the work area during the operation of the plant and after its decommissioning. The plan should describe what will be done to the borehole after the decommissioning of the plant, how the borehole is to be closed, if relevant, and the risks associated with doing so.

Geothermal drilling involves extensive use of traditional rotary drilling techniques, as well as various hammer drilling techniques. Factors that increase the cost of drilling in geothermal projects include the need to drill in hard, crystalline rock, drilling depth and targeted boreholes. The boreholes to be drilled are large in diameter and have high flow rates. The boreholes are cased and cemented to prevent them from collapsing. Since the aim is to produce heat, the drilling and borehole scanning equipment and the casing material used should withstand high temperatures and pressures, as well as the chemicals that may be used in the borehole. The operator is responsible for ensuring that the casing and cementing are adequate and undamaged. (Finger and Blankenship 2010; Hirschberg et al. 2015.)

Drilling techniques that are more effective than traditional rotary drilling include pneumatic hammer drilling and hydraulic hammer drilling, which involve using gas or drilling mud to cool down the drill bit, lift drilling waste out of the borehole and prevent the borehole from collapsing before it is cased. In these techniques, the fluids used usually consist of chemically enhanced mixtures optimised for the rock being drilled and for the drilling technique used in terms of density and viscosity, for example (Hirschberg et al. 2015). In addition to hammer drilling, some projects have also adopted more modern techniques, such as plasma drilling. The sector is experiencing rapid growth, thus this report is not covering all the available techniques.

The work site plan should describe the planned drilling technique; the drilling equipment and its requirements, the materials and dimensions of the pipes to be installed in the borehole, the pumps to be used and planned injection volumes, drilling pressures, any chemicals to be used in the drilling and their handling thereof, and the management of the waste generated during drilling. In addition to this, the plan should describe the potential “cellar facilities” required for the upper part of the borehole and any other structures planned for the upper part of the production borehole.

Any amendments made to the plans during work, such as any additional cementing or the rotary drilling of weakness zones, must be reported to the relevant supervisory authority after the work.

5.4 Communications plan

The benefits and potential risks associated with geothermal power production are not generally well-known, and thus public approval is a major challenge for operations. Generally, the less the general public knows about the project, the more negative their impression of it (Wiemer et al. 2017). Providing the public with information about cooperation with the authorities and the backgrounds of cooperation partners increases trust. Thus it is usually beneficial for the operator to inform the public who is supervising the project for public safety and which parties will be informed about.

The permit application should preferably include a communications plan, describing the timetable of communications targeted at different interest groups and the communications channels to be used. The plan should also specify the party responsible for communications and detail how the communications will be handled throughout the project. The plan should include an estimate of the area of effect of induced seismicity. The general communication should be targeted to the area, across municipal boundaries, if necessary. The plan can also include a timeline describing how communications with different parties will be handled as the project progresses. The interest groups/parties that should be covered in the communications plan include:

- **Permit authorities:** The communications plan should specify the level of communications with permit authorities as the project progresses, including more detailed timetables, project plans (pertaining to fluid injection, among other things) or information about exceptional situations during the project.
- **The party supervising seismic monitoring:** A communications timetable and the communications channels to be used should be agreed upon with the supervisory party before the commencement of the project. In the active construction phase (drilling and stimulation),

the supervisor should be informed of any exceptional situations, such as exceedances of TLS thresholds, immediately after the associated seismic analysis is complete. The supervisor should also be informed of any changes in operating parameters and timetables and any long-term disruptions in the seismic network.

- **The Institute of Seismology** monitors seismic activity in Finland and is the party that people contact about earthquakes, blasts and other vibration observations. Because of this, the Institute of Seismology must be informed of any geothermal projects. The Institute should preferably be provided with some information about the project before construction begins. The Institute should be provided with the contact information of the person/team responsible for the project's communications and with information on where inquiries about induced seismic events should be directed to (e.g. the project's website).

- **Operators that use sensitive equipment** (hospitals, research institutes, etc.) and **sites that are historically valuable or otherwise sensitive to damage** (Section 5.1) should be contacted when the location of the plant is being planned. The communications plan should specify how these parties should be informed in exceptional situations of threshold exceedance.

- **Local safety authorities:** Following the largest seismic events, the local population may also contact emergency response centres. Rescue authorities and the police, if necessary, should be informed about the project before drilling and stimulation. In pre-consultation, it should be agreed upon, how and in what kind of exceptional exceedance situations they should be notified.

- **People living and working in the area of effect** should be informed about the project before drilling and stimulation. The communications plan should define the target area and what communications channels are to be used. This may include for instance public events, the press and the Internet, among others. The project should have an active Open Access information channel (such as a website or social media) for providing information on the progress of the project and on any exceptional situations, such as exceedance of seismic threshold values, at least for the duration of the stimulation phase.

6. Recommendations for the monitoring and supervision of the operation

Monitoring recommendations depend on the operating principle of the geothermal plant. The seismic risk associated with a fully enclosed geothermal well, in which the circulating fluid does not come into contact with the rock, is small. These types of plants do not require seismic risk analysis or seismic monitoring. However, seismic monitoring may increase trust and transparency, especially if the public has expressed opposition to or concerns about the project. (Wiemer et al. 2017.)

If the heat transfer method of the geothermal plant involves fluid coming into contact with bedrock, the seismic risk is higher, in which case operations must be monitored. If the construction of the plant involves stimulation, the seismic risk is even higher, and the seismic monitoring must be scaled accordingly. A correctly scaled seismic monitoring system makes it possible to locate all possible induced earthquakes and to determine whether they were caused by the plant or not. The monitoring network should remain operational throughout all the phases of the plant's operation, as well as after its decommissioning.

The monitoring recommendations presented in this section are divided based on the different phases of a plant's lifecycle and further into seismic risk monitoring and other environmental monitoring.

6.1 Construction phase

The construction phase consists of the drilling and possible stimulation of boreholes.

Seismic monitoring

As described in Section 4.4., the seismic monitoring network should be set up well in advance of the construction phase, as the testing of the stations and the determination of the level of background seismicity requires a monitoring period of 1–6 months. Online data connections to the servers of the supervisory party and the Institute of Seismology must be operational before drilling commences. It is recommended that the central station be equipped with both an accelerometer and a seismometer. If the project involves stimulation, accelerometers should also be installed at sites with sensitive equipment or other special requirements.

During drilling, the real-time monitoring network, automatic analysis system and data connections must all be operational. The manual analysis of seismic events is carried out during normal working hours.

During stimulation, the seismic risk management requires real-time monitoring of seismic activity and fast data connections and communication channels between different project parties. Exceptional situations require also quick communication with various authorities and, once the analysis is completed, communication to the public. Monitoring must be operational and standby readiness maintained around the clock, and manual analysis must be performed immediately after threshold values are exceeded. The operator is responsible for the service reliability of the monitoring stations and the data connections throughout the project, but especially during exceptional situations.

After stimulation, the next phase of the project is controlled depressurisation, during which some plants have experienced their largest earthquakes (see Table 1). Generally depressurisation decreases the number and size of earthquakes, but because the pressure is not released evenly, it may also induce earthquakes. Because of this, the real-time monitoring network, its data connections and the automated analysis system must remain operational until the level of seismic activity returns to its natural background level, or at least for 6 months. The operator is responsible for the manual analysis of any exceedance of traffic light system's threshold values and the reporting thereof during normal working hours.

Environmental monitoring

Any functions that have been identified as or can be suspected of causing environmental risks or significant changes in environmental conditions must be monitored during the drilling phase. The associated monitoring plan must be included in the permit application. Factors that must be monitored in particular include noise, radiation, waste management, chemical consumption and the state of groundwater. The monitoring plan should describe how monitoring is to be carried out, including implementation timetables and the reporting of results.

6.2 Production phase

Each plant must keep a logbook based on which its operations are monitored and the plant is serviced. The information gained as a result of the monitoring of the construction phase is taken into account in the updating of the monitoring plan.

Seismic monitoring

During the production phase, seismic activity typically decreases, but seismic risk remains elevated. Seismic monitoring is conducted by using the same network of monitoring stations and automated analysis system that were used in the stimulation phase. Any exceedance of the traffic light system's threshold values are analysed manually and reported during normal working hours. The monitoring plan is updated as necessary. Even if the monitoring network is scaled down, at least one seismic monitoring stations connected to the national network should remain operational.

Environmental monitoring

The monitoring plan is updated as necessary or environmental monitoring can be discontinued during production, provided that no significant environmental impacts are observed or previously observed environmental changes have reverted back or close enough to their natural level. The permit authority is responsible for approving any changes in monitoring and the discontinuation thereof at the operator's request.

6.3 Follow-up monitoring

The decommissioning of the plant is carried out according to a decommissioning plan, which must specify what is to be done to the drilled boreholes and injected fluid. The follow-up phase also includes the demolition of the plant and the restoration of the environment to a state corresponding to the planned land use of the property.

Seismic monitoring

There are some known cases where sealing of a borehole after the decommissioning of a plant has increased pore pressure, which has induced seismicity. It is recommended that the network of seismic monitoring stations used during the production phase remain in operation for at least 6 months after the decommissioning and depressurisation of the plant. If seismic activity continues beyond this, seismic monitoring should also continue accordingly.

Environmental monitoring

If no significant environmental impacts were observed during the monitoring of the production phase or if monitoring was discontinued based on justified grounds during the production phase, there is no need to carry out environmental monitoring during the follow-up phase. If, however, the production phase caused impacts that result in an obligation to carry out environmental monitoring, the monitoring should continue after the production phase until the environmental changes have reverted back to an acceptable level. The matter must be agreed upon separately with the permit authority.

7. Summary

This report presents basic information about different forms of geothermal energy and the risks associated therewith. Furthermore, the report presents recommendations concerning the content of plant permit applications and the monitoring of the different phases of a plant's operation.

A permit application for a geothermal plant should include:

1) Background studies assessing the suitability of the area for plant use and the area of effect of the plant:

   - The operating principle of the plant: does the injected water come into contact with bedrock, and does the construction phase of the power plant involve stimulation? The operating parameters: volume, flow rate, pressure and temperature of injected fluid.

   - Orientation and magnitude of the stress field in relation to existing faults. Extent and rock mechanical characteristics of the faults.

   - Local geology, rock types and their mechanical properties. Hydrogeological properties, such as the porosity and hydraulic permeability of the rock, pore pressure and groundwater areas.

2) Assessments related to induced seismicity

   - Survey on permissible levels of ground vibration

     A review of local building codes and regulations concerning permitted ground vibration levels. A survey of the local soil type and any infrastructure with special requirements concerning ground vibration.

   - Seismic hazard and risk assessment

     Determination of the area's natural seismic hazard and induced-seismicity hazard caused by operations: survey of the background seismicity, preparation of a seismic hazard assessment (PSHA and/or DSHA), estimation of the level of seismicity induced by water injection.

     Preparation of a seismic risk assessment based on the hazard and survey of areas, buildings and settlements susceptible to earthquakes.

3) Environmental impact assessment

   - Land use, impact on the area's geology and any nature sites

   - Impact on surface water bodies and groundwater

- Management of drilling waste, dust and potential radioactive matter
- Noise and vibration nuisances during construction
- Traffic arrangements
- Chemical handling
- Assessment of the energy efficiency and climate sustainability of the plant

4) Monitoring and contingency plan

- It is recommended that the authority responsible for the operating area of the plant appoint an independent party to supervise the implementation of the seismic monitoring system. The Institute of Seismology must be kept informed about the operating phases of the project.
- A description of the seismic monitoring network, the analysis and traffic light system and the delivery of real-time data to the supervisory party and the Institute of Seismology.
- An assessment of the environmental risks associated with operations, preparation for them and a plan of action for potential accident situations.

5) Work site plans for the drilling and the actual operation phase

- The use of the work site and functions therein, identification of occupational health and safety risks and a plan for the mitigation thereof.
- Description of the planned drilling technique, the requirements thereof and any chemicals to be used in drilling and the handling thereof.

6) Communications plan

- A list of the parties with whom communications are to be carried out: different permit authorities, parties responsible for seismic (and other, if necessary) monitoring, the Institute of Seismology, safety authorities, local residents and operators, sites sensitive to vibrations.
- The means by which communication with different interest groups is to be carried out and of how communications are to be handled in general and in exceptional situations.
- The area of effect of communications and municipal boundaries.

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Appendices

Appendix 1: Observation report material

Observation reports received by the Institute of Seismology during the stimulation phase of the Otaniemi geothermal plant project.

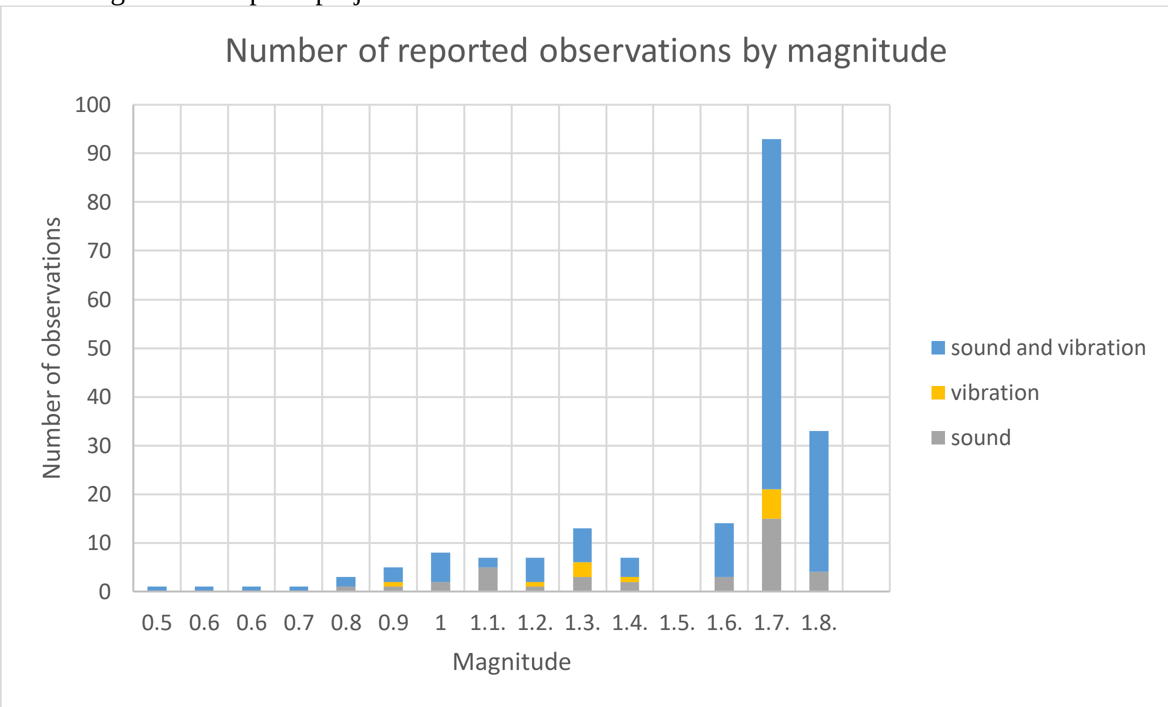

Figure 16

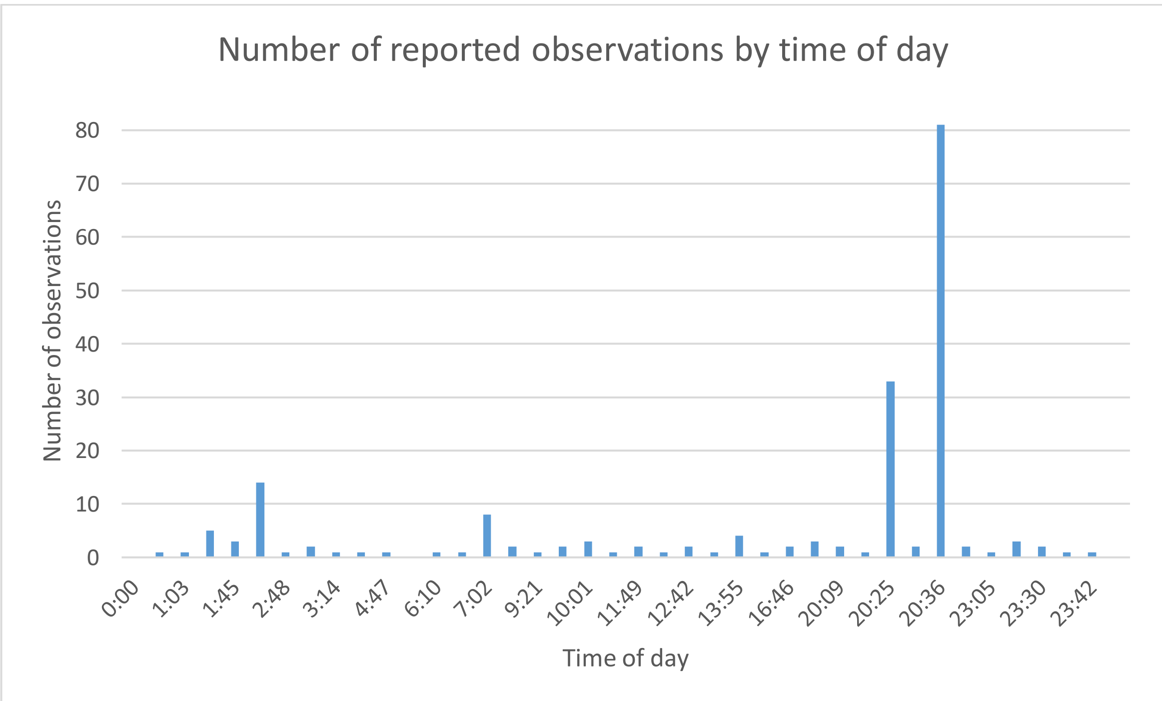

Figure 17

Table 3: Earthquake observation reports from the stimulation phase of Otaniemi's 1st borehole

Date	Time	Magnitude	Total number of observations	Sound	Vibration	Sound and vibration
7 Jun	23:42	1.0	1	0	0	1
9 Jun	8:42	1.1	2	2	0	0
14 Jun	3:22	1.0	1	1	0	0
20 Jun	3:13	1.3	2	2	0	0
20 Jun	2:27	1.6	14	3	0	11
21 Jun	20:56	1.2	2	0	1	1
23 Jun	9:21	1.1	1	0	0	1
23 Jun	11:59	1.1	1	1	0	0
29 Jun	7:02	1.7	8	1	0	7
29 Jun	12:42	1.3	2	0	1	1
30 June	9:53	1.4	2	1	0	1
3 Jul	0:51	1.0	1	0	0	1
3 Jul	23:11	1.0	3	1	0	2
3 Jul	23:30	1.1	2	1	0	1
4 Jul	3:14	1.0	1	0	0	1
4 Jul	4:47	0.9	1	0	0	1
4 Jul	6:46	1.0	1	0	0	1
5 Jul	10:01	1.4	3	1	0	2
6 Jul	11:49	1.4	2	0	1	1
7 Jul	20:32	1.2	2	0	0	2
8 Jul	10:09	0.6	1	0	0	1
8 Jul	12:52	0.5	1	0	0	1
8 Jul	20:36	1.7	81	13	6	62
12 Jul	17:25	1.3	3	0	2	1
12 Jul	23:36	0.9	1	0	1	0
13 Jul	16:35	1.3	1	0	0	1
15 Jul	23:05	0.7	1	0	0	1
16 Jul	20:25	1.8	33	4	0	29
18 Jul	20:09	0.8	2	0	0	2
19 Jul	1:45	1.2	3	1	0	2
19 Jul	13:55	1.7	4	1	0	3
21 Jul	16:46	0.9	2	1	0	1
22 Jul	6:10	0.8	1	1	0	0
22 Jul	20:15	0.6	1	0	0	1
23 Jul	1:03	0.9	1	0	0	1
24 Jul	1:03	1.3	5	1	0	4
24 Jul	2:48	1.1	1	1	0	0

Appendix 2: GRID

Geothermal Risk of Induced seismicity Diagnosis (GRID) is a tool for managing the risk of induced seismicity, which can be applied to all geothermal energy projects in conditions similar to those in Switzerland (Trutnevyte and Wiemer 2017). While the GRID process can be utilised in all stages of the project, it yields the greatest benefits in the planning stage. The system revolves around scoring geothermal projects in three different areas: 1) **Induced seismic hazard**, which encompasses the operating parameters of the plant and the seismic hazard of the area. 2) **Other areas of seismic risk**, meaning housing in the area, its vulnerability to earthquakes, the amplifying effect of the soil, the sensitivity of infrastructure and the secondary hazards resulting from earthquakes, such as landslides and tsunamis, fires, etc. For the sake of brevity, this is referred to in the tables as risk, even though in this context the term does not include seismic hazard. 3) **Social concern**, which is based on the perception of the area's residents and operators. Table 4 presents the different areas and indicators used to evaluate GRID according to the original model. Each indicator is assigned a value between 0 and 2. Switzerland is an area of higher seismic activity than Finland, and the local seismic risk is taken into account in the country's building codes. As such, GRID is not directly applicable to Finland. For example, the hazard level assessed based on the rock type is always high in Finland, as the soil layer on top of the bedrock is thin nearly everywhere in the country.

The indicators of seismic hazards and risks are summed up and depicted on the GRID graph in accordance with Figure 18. The indicators of social concern are summed up as well and increase both the seismic hazard score and the seismic risk score by 0.5 per each point of social concern. The line segment in Figure 18 illustrates how much emphasis the GRID model places on social concerns.

*Table 4: Indicators used in the Swiss GRID model. * 2 nearly everywhere in Finland. ** The categorisation is based on a Swiss standard that does not have an equivalent in Finland. The table was prepared according to Swiss conditions and is, thus, not directly applicable to Finland.*

score	0 (little concern)	1 (medium concern)	2 (high concern)
Seismic hazard concern			
Depth of the reservoir	<1 km	1–3 km	>3 km
Cumulative injection volume during stimulation	<1,000 m^3	1,000–10,000 m^3	>10,000 m^3
Daily injection or extraction volume during operation	<1,000 m^3/day injection or <5,000 m^3/day extraction	1,000–10,000 m^3/day injection or 5,000–50,000 m^3/day extraction	>10,000 m^3/day injection or >50,000 m^3/day extraction

score	0 (little concern)	1 (medium concern)	2 (high concern)
Rock type	Sediments / soil	Within 500 m metres from the crystalline basement	Crystalline rock / bedrock *
Separation between background and induced seismicity **	≤0.6 m/s^2 dimensioning value	0.6–1.3 m/s^2 dimensioning value	≥1.3 m/s^2 dimensioning value
Fluid injection pressure	<0.1 MPa	0.1–1 MPa	>1 MPa
Distance to known and potentially active faults	>5 km	2–5 km	<2 km
Seismic risk, exposure and vulnerability of the area, secondary hazards			
Local site amplification within a radius of 5 km	No buildings or infrastructure on soft soils	<10% of buildings or infrastructure on soft soils	≥10% of buildings or infrastructure on soft soils
Exposed population within a radius of 5 km	Remote: <100 inhabitants	Rural:100–20,000 inhabitants	Urban: >20,000 inhabitants
Industrial or commercial activity within a radius of 5 km	Low activity	Medium activity: ≥1 enterprises with 100–499 employees or ≥1 industrial installations	High activity: ≥5 enterprises with 100–499 employees or >1 enterprises with over 500 employees or ≥2 industrial installations
Importance of buildings and infrastructure within a radius of 5 km **	No buildings or infrastructure of Class II or III *(no important buildings)*	Buildings or infrastructure of Class II *(important buildings)*	Buildings or infrastructure of Class III *(very important buildings)*
Infrastructures with considerable environmental risk	None	–	One or more
Unreinforced cultural heritage	<5% of buildings	5–10% of buildings	>10% of buildings or an internationally important heritage site
Susceptibility to secondary hazards within a radius of 5 km	Very low	Exists	High

score	0 (little concern)	1 (medium concern)	2 (high concern)
Social concern			
Potential for concern in the general population	None	Exists	Significant
Vulnerable or strongly opposing stakeholders	None	Exists	Significant
Negative experiences with similar projects	None	Exists	Significant
Lack of trust in the project operators of authorities	None	Exists	Significant
Benefits to the local community	Direct benefits with or without monetary compensation	Monetary compensation only	None

There should be at least three parties involved in the GRID scoring: the operator, the permit authority responsible for the operating area and one or more independent experts. Based on the scoring, projects are categorised into four different risk categories, each of which is associated with different recommendations for monitoring and communications.

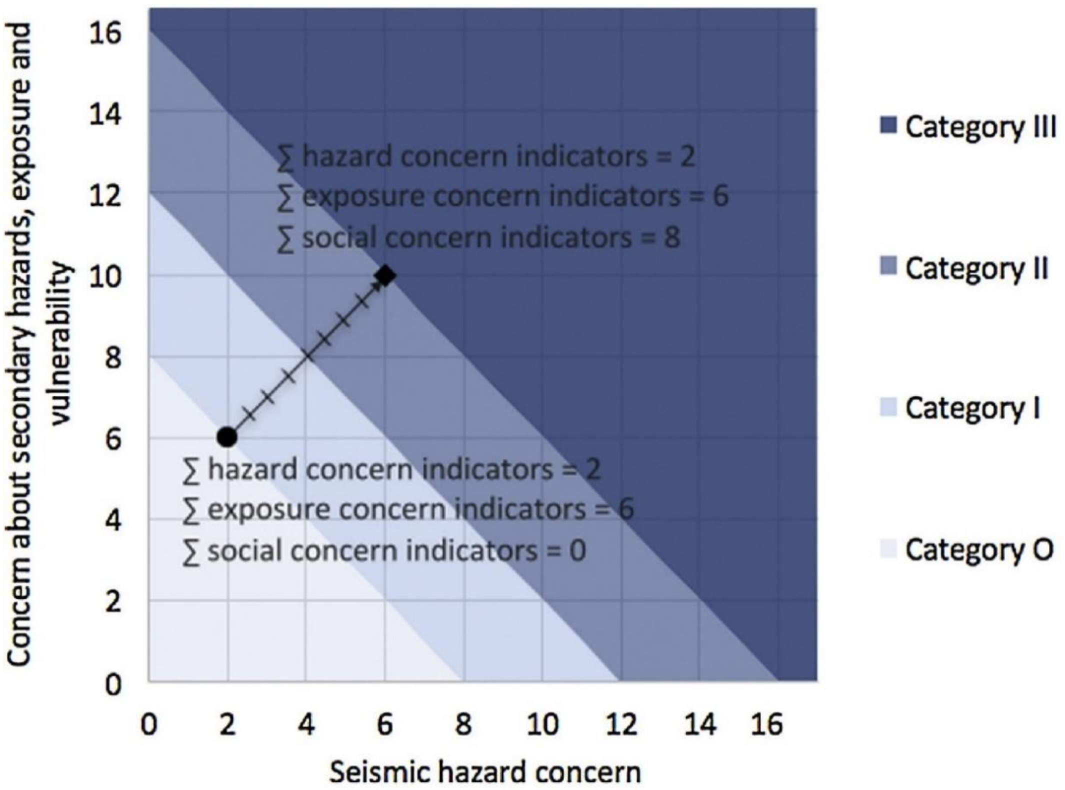

Figure 18: Visualisation graph for GRID results. Source: Trutnevyte and Wiemer (2017, Fig. 2).

- **Category 0:** Induced seismic hazard, risk and social concern are very low or absent and no dedicated induced seismicity risk governance is needed. Typical category 0 projects are, for example, ground source heat wells and enclosed systems in which the heat exchange fluid does not come into contact with the rock.
- **Category I:** Induced earthquakes may occur, but damaging events are very unlikely and there is no significant social concern to be addressed. Typical projects in this category include various shallow (0.5–3 km) projects in existing aquifers, located in low-risk areas away from active seismic zones or faults.
- **Category II:** Induced earthquakes may occur, and damaging events and social concern cannot be excluded. Typical projects in this category include projects in existing aquifers with varying depths that do not involve stimulation, but are located in risk areas or can show evidence of social concern.
- **Category III:** Induced earthquakes are likely, damaging events and significant social concerns are possible and require thorough risk governance measures. Typical projects in this category include projects that involve stimulation, projects in depths below 3 km or in crystalline rock and projects in seismically active areas or near active fault systems.

The recommended induced seismicity risk governance measures prepared for the area of Switzerland based on these categories are summarised in Table 5. The Table should be tailored based on the conditions in the country in question.

*Table 5: Summary of recommended risk governance measures for different categories. For more information on risk assessment, please refer to Section 4.3 of this report. For more information on communications, please refer to Section 5.4 of this report. For more information on seismic monitoring and the traffic light system, please refer to Section 4.4 of this report. * Two-way engagement means the hearing of interest groups. For more information on all of these measures, please refer to the original publication.*

	Category 0	**Category I**	**Category II**	**Category III**
Initial hazard and risk assessment	none	empirical, scenario-based hazard assessment	empirical, scenario-based hazard and risk assessment	probabilistic hazard and risk assessment
Social site characterisation	none	voluntary	necessary	necessary
Information and outreach on induced seismicity	none	necessary	necessary	necessary
Two-way engagement *	none	voluntary	necessary	necessary
Insurance and liability	none	necessary	necessary	necessary
Structural retrofitting	none	optional	optional	necessary to consider
Seismic monitoring	none	single station	seismic network	seismic network
Traffic light system	none	voluntary magnitude-based	magnitude-based	adaptive, in parallel to magnitude-based

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